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Tracking Seasonal and Storm Induced Recession of the Popham-Seawall Barrier Beach Complex, Phippsburg, Maine

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Bates College Geology Department Thesis

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By

Amanda Lee Wescott

Lewiston, Maine
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“The sea, once it casts its spell, holds one in its net of wonder forever.”

-Jacques Yves Cousteau

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Abstract

The Popham-Seawall complex, located at the mouth of the Kennebec River in Phippsburg, mid coast Maine, is a dynamic, transgressive barrier beach system. In recent years, the migration of two main tidal inlets in the barrier system has played a major role in increased beach erosion at Popham Beach State Park and on the pocket beaches of Cape Small. Changes in the Seawall barrier in recent years have been minimal, however since 2010, landward recession of the frontal dune ridge has become apparent. The purpose of this study is to document physical changes along the barrier complex, pocket beaches and associated tidal inlets, from summer 2012 through winter 2013, and compare the influence of storm events and seasonal weather patterns on the geomorphology of the entire complex.

Detailed seasonal and storm-induced changes on the beach system were documented by topographic profile survey, high resolution GPS tracks, and net sand migration analysis. Longer term (annual) changes were documented using high resolution georeferenced satellite imagery and air photographs.

Beach front at Popham Beach State Park has undergone sustained, documented erosion since 2007 when the Morse River migrated towards State Park beaches with the eastward longshore growth of the Seawall Barrier spit. Although the long Seawall spit was breached by avulsion of the Morse River in 2010, erosion has continued along the beach front. Analysis of the net sediment transport shows extensive erosion as summer transitions into fall, with 1763m^3 of net sand loss to the West Bath House shore front.

Likewise, pocket beaches at Cape Small are continually eroded by the westward shift of the Sprague River, forced against the Cape Small headland by the westward development of the southwestern Seawall spit. Recent changes in the 2.25 km-long Seawall barrier beach are evident with up to 15m of landward migration of the frontal dune ridge in many sectors of the beach since 2009. As a result of Hurricane Sandy and the winter storm Athena, beginning on October 28th and November 7th respectively, enhanced longshore sediment transport was documented with 2256 m^3 of sand accreting onto the shore face at the W15OO transect, located directly up drift next to the southwestern Seawall spit, indicating continued spit growth via displaced sand.

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Chapter 1
Introduction

(Wescott, 2012)

1.1 Purpose

Coastal settings around the world are characterized as highly active environments with various geomorphic processes interacting all at once. Sandy barrier beach systems are dynamic systems which are constantly evolving. The development of these systems are influenced by both long and short term factors. Long term influences such as sea level rise and climate change have lasting effects on the physical appearance and morphology of the beaches. However, seasonal weather patterns and storm events are short term events which highly impact beach formation through erosion and accretion (Hill et al., 2004) Recently, global warming has induced sea level to rise by 3.1 +/- .7 mm per year since 1993 (FitzGerald et al., 2008 and IPCC, 2007) and ultimately increases storm magnitude, damage, and erosion of vulnerable low-lying coastal beach systems. The coast of Maine is dotted with barrier beach complexes, resulting from the region's structural geology and the state's glacial history (FitzGerald et. al, 1989). In recent years, the complex barrier systems associated with the Kennebec River estuary, the Popham and Seawall beach complexes have experienced severe morphological alterations along with expedited transgression. Furthermore, the region has been experiencing changes since the late Holocene, when sandy shorelines transgressed landward and altered physical setting and location (Barnhardt et al., 1995). In addition to the influence of SLR, seasonal storms and weather patterns influence control on sand migration throughout the barrier systems in Phippsburg (Fenster et al., 2001). These storms enhance inlet migration and sand transport, causing increased erosion to the beach front.

Kelley et al. (1993) state that modern rates of sea-level rise have begun to accelerate. This increase of SLR is, similar to before, causing erosion and allowing for further landward transgression by the barrier systems, specifically in Phippsburg, ME. However, beaches now suffer from human influence. Coastal areas account for 10% of the world's population (FitzGerald et al., 2008), and therefore the construction of seawalls, coastal road systems, and beach front structures increase storm and weather related erosion occurring on these barrier systems. In order to prevent possibly permanent, detrimental alterations to the morphology of the system, which is enhanced through development, the dynamics of the beach systems must be understood.

This study primarily focuses on tracking the current migratory patterns of sands and associated morphological changes of the Seawall and Popham Barrier beach complexes. Surveying, time lapse photography, and GPS tracking conducted from June 2012 through February 2012 record these morphological changes which are influenced by seasonal weather and storm events, as well as increasing rates of SLR. To give the research context, current data sets must be compared to various historical ones.

1.2 Physical Setting

1.2.1 Location

Phippsburg, ME, is located in the south-central coast of Maine along the Phippsburg Peninsula (Buynevich et al., 2004) (Figure 1.1), in the rocky indented coastline compartment that is characterized by long peninsulas, island chains, and shoals all separated with narrow estuaries and bays (FitzGerald et al., 2000 and Kelley et al., 1993). This geomorphic setting is perfect for sand deposits to anchor onto and develop into expansive sandy beach systems, backed with extensive tidal marshes (Kelley et al., 1993). Part of the study area is preserved through the 574 acre Bates-Morse Mountain Conservation, a co-op which is owned and managed by the St. John's Family, Bates College, and the Small Point Association (SPA) . The plot of protected land encompasses the dunes along Seawall Beach back to Route 216, and is bounded on the west and east by the Sprague and Morse River banks.

The Popham-Seawall complex is confined by the bedrock of Small Point to the west and by the mouth of the Kennebec River estuary to the east (Figure 1.2). The pocket beaches, Little beach and Ice Box Beach, are anchored against the western most bedrock of Cape Small while Popham Beach, comprised of Riverside, Hunnewell, and State Park shorelines, is farthest east and terminates at the mouth of the Kennebec River Estuary. Seawall Beach is separated from the pocket beaches and Popham by two migratory tidal inlets, the Sprague and Morse River inlets. These inlets link the extensive back-barrier marshes to the shoreline, creating two mini estuaries west of the larger Kennebec estuary. The beach system is exposed to strong winds and waves approaching from the northeast during winter 'Nor'easters' (FitzGerald et al., 2000), causing much of the sand migration throughout the complex. However, the system is protected from the habitual southwestern waves and winds by various islands, offshore ledges, and by Cape Small itself (FitzGerald et al., 2000) and thus major morphological alterations occur in the winter months rather than summer, early fall, and late spring.

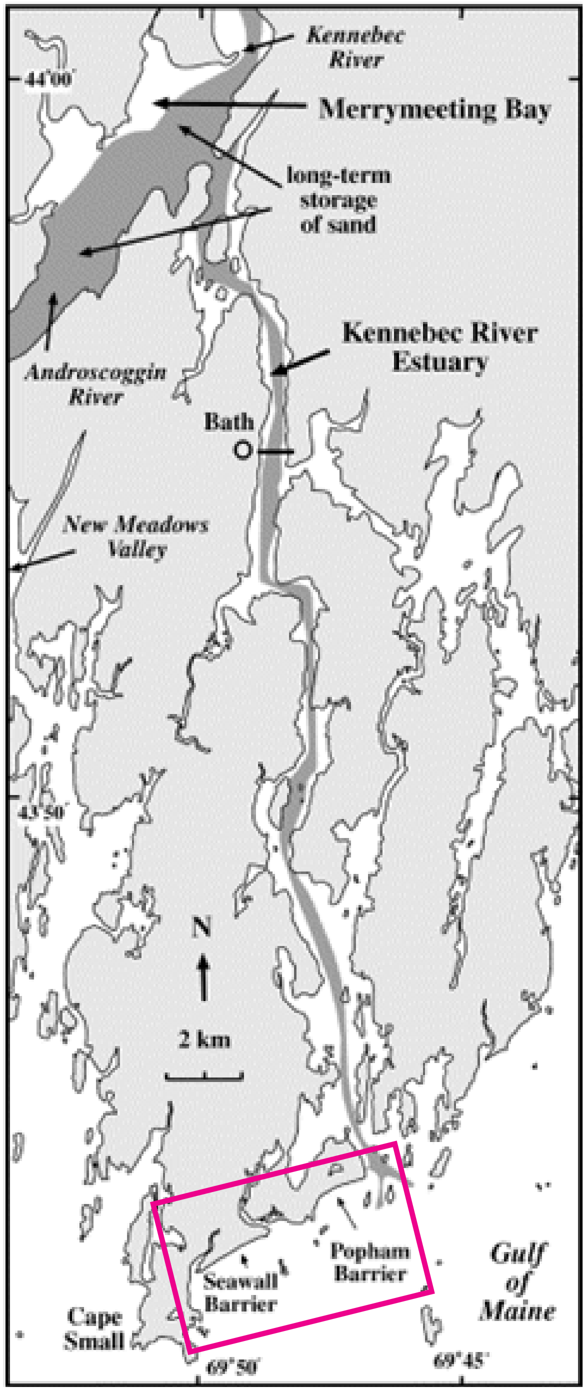


Figure 1.1: Map view image of Phippsburg Peninsula indicating location of study zone in pink box, about 22 Km south of Bath, ME. The area is characterized by long, narrow estuaries and bays including the Kennebec River Estuary highlighted in dark grey (FitzGerald et al., 2000).

Figure 1.2: location map of study zone. Study site includes 4 beaches in Phippsburg, ME, part of the South-Central compartment of Coastal Maine. The barrier system is confined by the Cape Small headland to the west and by the mouth of the Kennebec River Estuary to the east (Image modified from QuickBird Satellite, 2010).

1.2.2 Bedrock Geology

The New England coast is comprised of bedrock dating back to the Precambrian and Mesozoic age that is highly metamorphosed, specifically within the south-central coastal region (Kelley et al., 1993) (Figure 1.3). Bedrock geology was extensively mapped by Osberg, Hussey, and Boone in 1985, and revisited in 2002 by Loiselle and Marvinney (MGS, 2002). These mapped features of the study zone were described by FitzGerald et al. (1989) as a, "high-grade metasedimentary fold belt that strikes in a northeast-southwest direction". Buynevich and FitzGerald (2000) detailed this definition to an isoclinically folded belt consisting of Proterozoic-Ordovician metasedimentary and metavolcanic rock intruded by Devonian granites and pegmatites.

Small Point in Phippsburg, ME, is comprised of three rock units which are sub units of the 'Casco Bay Group'. The Scarboro, Diamond Island, and Cape Elizabeth Formations were deposited during the Ordovician, and underwent metamorphism in the Devonian-Silurian, (Covill, 1980). The Scarboro Formation is comprised of sulfidic to non-sulfidic mica rich schists containing some garnets and rare amphibolite beds. The Diamond Island

Formation is a sulfidic, quartz-graphite-muscovite rich phyllite. The Cape Elizabeth Formation is described as a gray, rusted, mica-quartz-plagioclase bearing schist with thin inter beds of Scarboro Formation . The Cape Elizabeth Formation underlies the majority of Seawall Beach, while the Small Point headland is mapped as mainly Scarboro and Diamond Island Formations (Covill, 1980). The local pluton, the Morse Mountain Pluton, intruded into the Cape Elizabeth Formation during the Middle Devonian, and is comprised of fine-coarse grained granites as well as pegmatites (Covill, 1980).

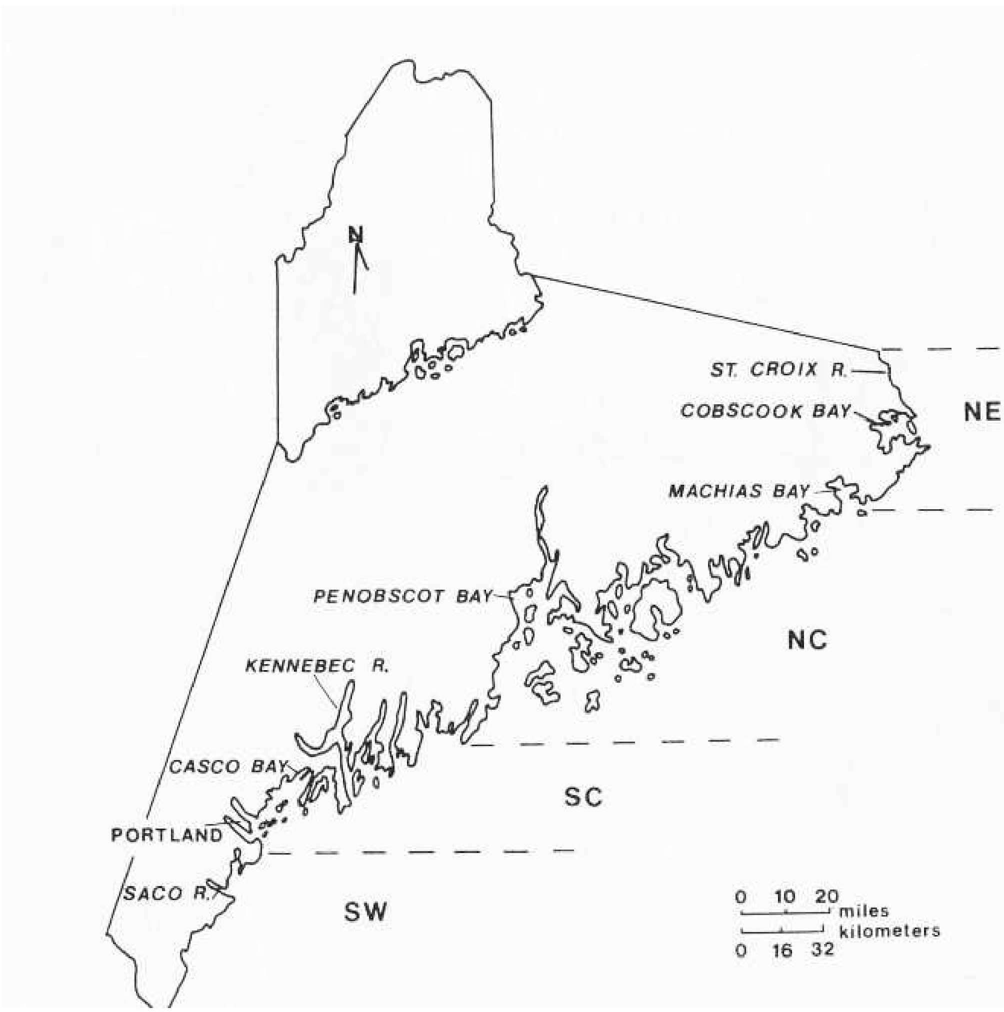


Figure 1.3: Bedrock geology of Maine compartmentalized into units with the study zone falling within the South-Central compartment, a highly metamorphosed and deformed marine sedimentary and volcanic unit (Kelley et al., 1993).

1.3 Barrier Complex History and Formation

1.3.1 Regional Glacial History

The location of Maine's present shoreline was determined by fluctuations in glacial activity throughout the late Quaternary, during which the most recent glacial maximum terminated, however, position is also a function of global sea level, and relocates accordingly.

Around 14 ka B.P., the Laurentide ice sheet retreated from its late Wisconsin maximum extent on the continental shelf near George's Bank (Retelle and Weddle, 2001) (Figure 1.4). During ice retreat, marine submergence of depressed crust, glaciomarine sediment was deposited inland of the present shoreline, marking the termination of marine submergence of Maine (Barnhardt et al., 1995). The glaciomarine deltaic deposits are described by Schnitker (1974) as till comprised of a poorly sorted mixture of angular gravels, sands, silts, and clays. Almost simultaneous with the retreat was the occurrence of isostatic rebound and coastal emergence, forcing regional sea level to rapidly drop, forming a low stand shoreline on the continental shelf off shore, containing marine sediment deposits (Barnhardt et al., 1995).

The sea-level low stand deposits are roughly 65m below present sea-level and mark the upper limit of the till deposits (Barnhardt et al., 1995, and Schnitker, 1974), and include the Kennebec River Paleodelta, an off shore sediment source for the Phippsburg barrier beach complexes. These marine deposits, marking the lower limit of marine regression during the period, consist of stratified layers of bluish-gray muds, sands, and clayey silts attributed to the Presumpscot Formation (Barnhardt et al., 1995, Fenster and FitzGerald, 1996, and Schnitker, 1974). Post emergence, sea level rose in episodic steps of accelerated and decelerated rates until reaching its present elevation (Barnhardt et al. 1995). The Gulf of Maine experienced episodic events of sea level rise and standstills until 5ka where SLR rates slowed until reaching current elevation and physical settings (Buynevich and FitzGerald, 2000) (Figure 1.5).

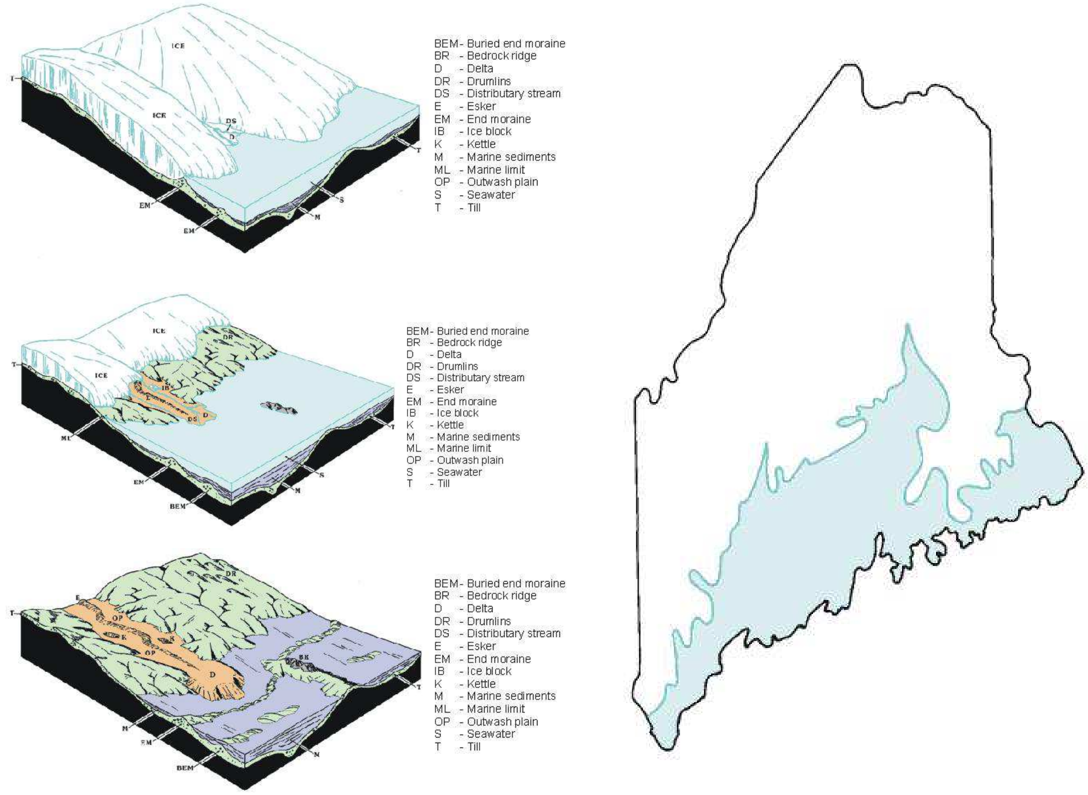


Figure 1.4: box model showing retreat of Laurentide ice sheet over Maine (left), and extent of Marine inundation before uplift 13,000 years ago (right) (Modified image from MGS, 2012)

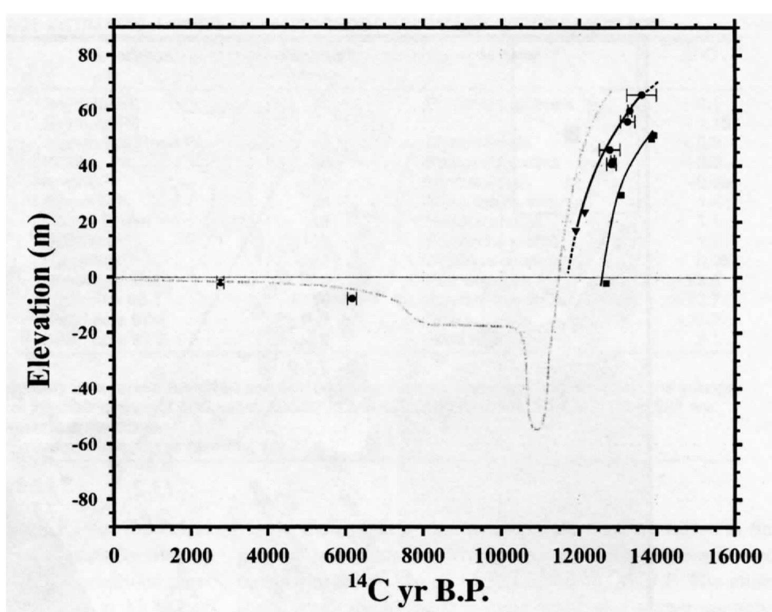


Figure 1.5: Regional relative sea level curves for state of Maine. Gray dashed line is the overall sea level curve for Maine, while the square marked line is from Eastern Maine, triangles are from islands in Casco Bay, and circles are from the Casco bay Lowland data set. (Retelle and Weddle, 2001).

1.3.2 Barrier Formation and Sediment Sources

The initial formation of the barrier beach complexes in Phippsburg, Maine began during a sea level stand still during the late Holocene, about 4-4.5 ka (FitzGerald et al., 2000). At this time sediment was abundant as marine deposits from previous transgressions, for example the Kennebec Paleodelta, were available to be eroded and reworked onshore (FitzGerald et al., 2000). This process developed the foundation for the barrier complexes studied today.

The Phippsburg beach systems continue to receive nourishment from the Kennebec River estuary. The coarse grained sediment contribution comes primarily from fluvial erosion of unconsolidated glacial ice-contact and periglacial deposits of the Kennebec River (Figure 1.6). The sand and gravel are eroded during high discharge, high flow velocity events, and then transported downstream. Once downstream, they are incorporated into the sediment gyre which exists between the estuary mouth, beaches, and offshore deposits (Fenster and FitzGerald, 1996; Fenster et al., 2001) (Figure 1.7). The river system erodes fine grained sediments from the upstream Presumpscot Formation, and later works it onto the barrier complexes through circulation of the sediment gyre system as well (Fenster and FitzGerald, 1996; FitzGerald, 2000).

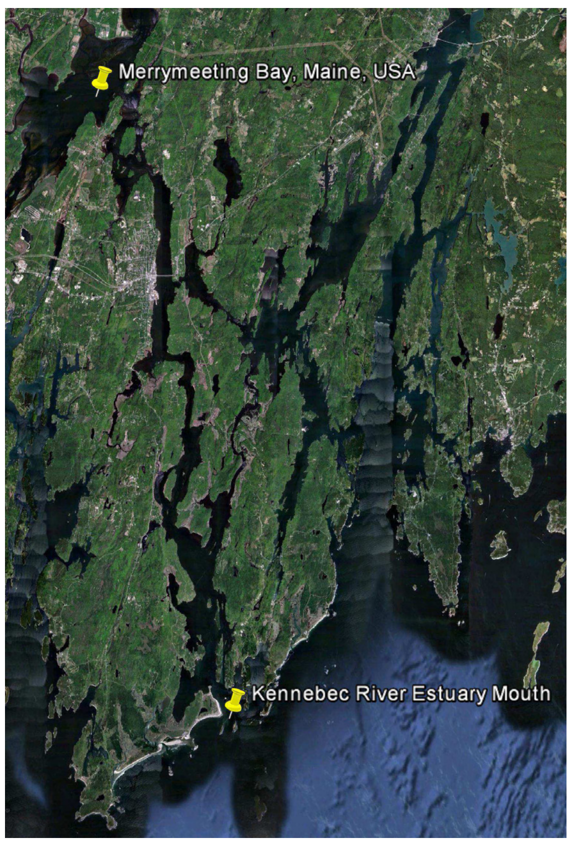


Figure 1.6: Merrymeeting Bay, the intersection of the Androscoggin and Kennebec River systems, is considered one of several possible sediment sources for the Popham-Seawall barrier complex (Fenster and FitzGerald, 1996), by transport of eroded bedrock material downstream to the study zone (Google Earth Pro, 2013)

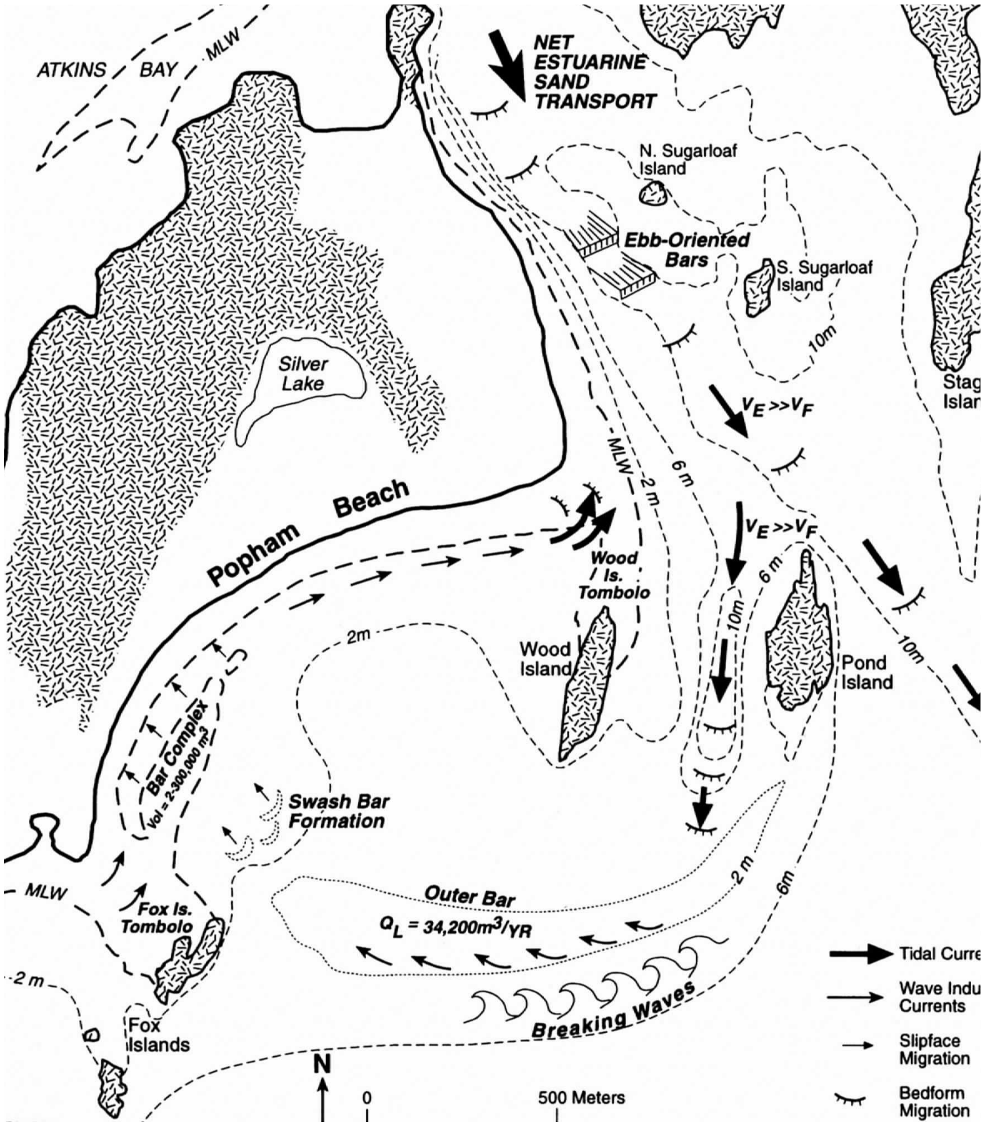


Figure 1.7: Popham Beach sediment gyre allowing for circulation and conservation of sediment within the barrier system despite storm events and seasonal, erosive weather patterns (Buynevich and FitzGerald, 1993; Fenster and FitzGerald, 1996; and FitzGerald et al., 2000)

Seasonal processes develop distinctive profiles of barrier beach systems biannually (Figure 1.8); a summer, constructive profile and a winter, erosional profile (Nelson and Fink, 1980). In the Gulf of Maine, summer months lack storm activity which tends to erode and carve away backshore features. Instead, the resulting low energy waves work offshore sand and sediment bars onto the beach, rather than removing it (Nelson and Fink, 1980). Therefore, the profile is a gradual transition from the dunes and berms all the way to the low tide terrace. Conversely, winter in the Gulf of Maine is characteristically stormy. Nor'easters bring strong winds and waves capable of eroding and transporting high volumes of sediment (Davis and Dolan, 1993). Beach profiles generated in the winter months show dramatic changes with carved dune scarps with little to no berm, which moves directly into the shore face and low tide terraces.

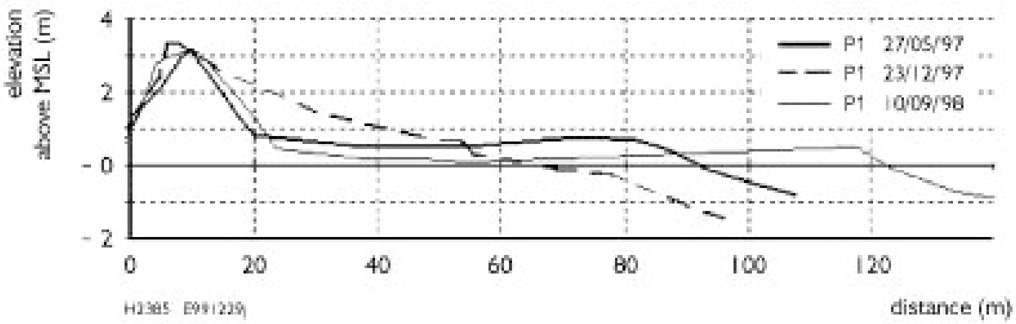


Figure 1.8: Generalized Beach profiles showing differences between a summer profile (solid line) to a winter profile (dashed line). (Stive et al., 2002).

1.4 Hydrographic Regime

1.4.1 Interaction of Wind, Waves, and Tides

Wind and waves are two forces acting simultaneously to transport sediment throughout barrier systems. Winds can transport sediment on their own via aeolian transport, or by interacting with the ocean surface to develop surface waves of specific height and course, corresponding directly to wind direction (Chandler, 2009). Data from the Seguin Island light house show that the strongest winds are generated by Nor'easters, and greatly affect tidal processes of sediment circulation near inlets, including long shore transport (FitzGerald et al., 1989) (Figure 1.9). However, strong winds have been documented as originating from the northwest and southeast as well (FitzGerald et al., 1989), and average wind direction in the area is from the south-south east during non-storm periods.

Winds act as a major force when generating ocean waves. Winds with intense speed and energy tend to generate powerful waves with proportionally larger wave height, energy and fetch. Breaking waves associated with strong north-northwesterly winds during Nor'easters are the most detrimental in terms of erosion (Figure 10). These waves move sand west from the barrier beaches onto off shore bars, which allow the sand to later be reworked onto the beaches when the bars are welded onshore. This cyclic reworking of the sand has been studied by FitzGerald (1989, 1996, 2000, 2001) and various other researchers, and has been defined as the local sediment gyre between offshore and onshore sources and the local estuary mouth.

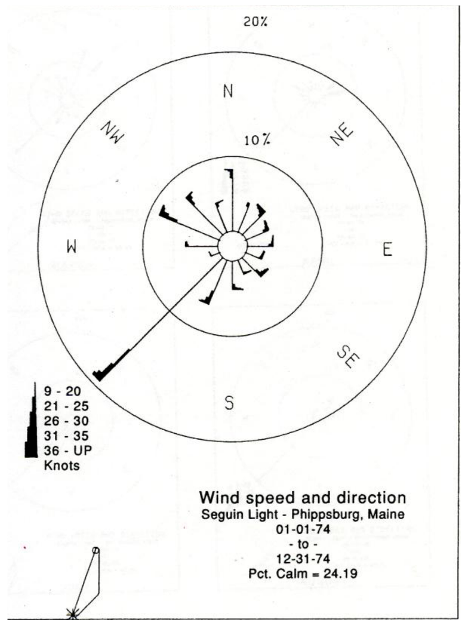


Figure 1.9: Rose diagram of wind speed and direction vectors reported from Seguin Island, ME. Indicates overall trends of southwesterly winds (FitzGerald et al. 1989).

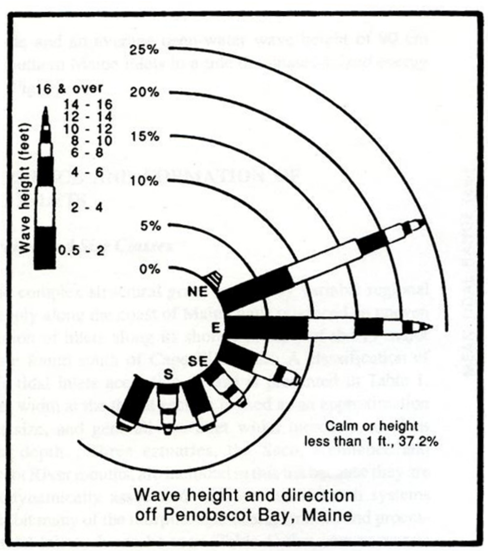


Figure 1.10: Rose diagram indicating wave height and direction vectors from Penobscot Bay, ME. Note that the largest wave heights are from the northeast, consistent with Nor'easters, strong winter storms (FitzGerald et al., 1989).

The coastline of Small Point is dotted with islands and offshore ledges, which produce a sheltering effect for the beaches by essentially refracting larger waves generated far off shore. This refraction forces the waves to have lesser energies and wave heights as they approach Small Point (FitzGerald et al., 2000) (Figure 1.11). Ultimately the waves are less damaging than those moving directly onshore, and FitzGerald et al. (2000) found that the waves which did not entirely dissipate on offshore bars or rock ledges produce westward flowing currents, aiding the welding of sand bars to nourish the barrier complexes. However, during normal conditions waves from the southwest and those refracted off Wood Island produce easterly longshore currents (FitzGerald et al., 1989; 2000). This is opposite of the westerly offshore currents generated through wave refraction on offshore bars, and these easterly currents relocate sediment to the river mouth (FitzGerald et al., 2000). Clearly tidal influence is a large factor in this sediment gyre, as the opposing easterly and westerly long shore currents effectively circulate sediment throughout the gyre. Although the Kennebec estuary is predominately ebb-tidal controlled, flow in the river is strong enough to reinforce these long shore currents (FitzGerald et al., 2000) and allow sand transport down drift to nourish the distal Seawall Complex.

Regional tides are semi diurnal deep water tides generated in the North Atlantic (FitzGerald et al., 1989) and work in conjunction with wave action to propagate the previously described sediment gyre. In Phippsburg, the flood tide duration is shorter than the ebb duration (Fenster et al., 2001) and they both have a mean tidal range of 2.6m, which increases up to 3.5m during spring freshet events (Fenster and FitzGerald, 1996) flushing riverine sediment into the gyre.

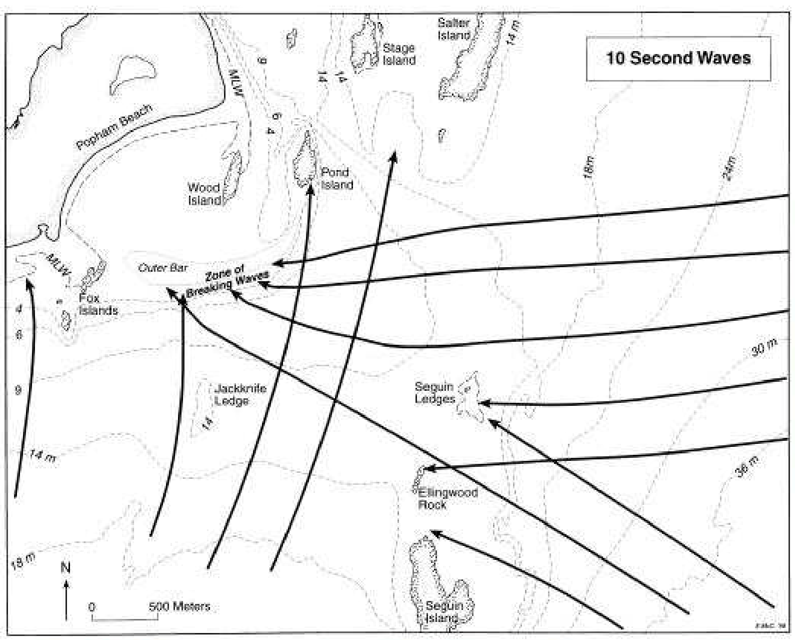


Figure 1.11: Wave refraction diagram showing the convergence of wave energy from the east, which results in overall westward longshore transport (FitzGerald, 2000).

1.4.2 Sea Level Rise and Storms

Other than gradual eustatic sea level rise, storm activity is mainly responsible for the major morphological changes occurring at barrier beach systems. Although sea level rise is effected by local processes, a mean rate of sea level rise at 1.7 mm +/- .5mm/yr (IPCC, 2007) (Figure 1.12) has been recognized internationally. Sea level rise induced by global warming is considered one of the most serious environmental threats of our age as over 634 million people live within 10m elevation of sea level (FitzGerald et al., 2008). Furthermore, over $3 trillion are invested in infrastructure and associated real estate along just the U.S. East Coast (FitzGerald et al., 2008). If sea level rise continues at such an accelerated pace, there is the potential for irreparable damage and insurmountable debt resulting from the inundation of low-lying coastal communities. Although the socioeconomic impacts of sea level rise are highly important and should not be taken lightly, the effects of which sea level rise will have on barrier islands similar to the Popham-Seawall complex are just as important. Zhang et al. (2002) found that beaches are able to recover to a long-term equilibrium under fair-weather, stable hydraulic conditions. However, as sea level rises, beaches cannot equilibrate to pre-storm conditions, as storms can cause drastic erosion over a short-period (Zhang et al, 2002). Instead, the complex feedback-dependant processes operating within the littoral zone that maintains barrier sediment budgets (FitzGerald et al., 2008) are thrown out of sync with sea level rise, and sediment is extracted permanently from the system, causing beach degradation despite fair-weather hydraulics.

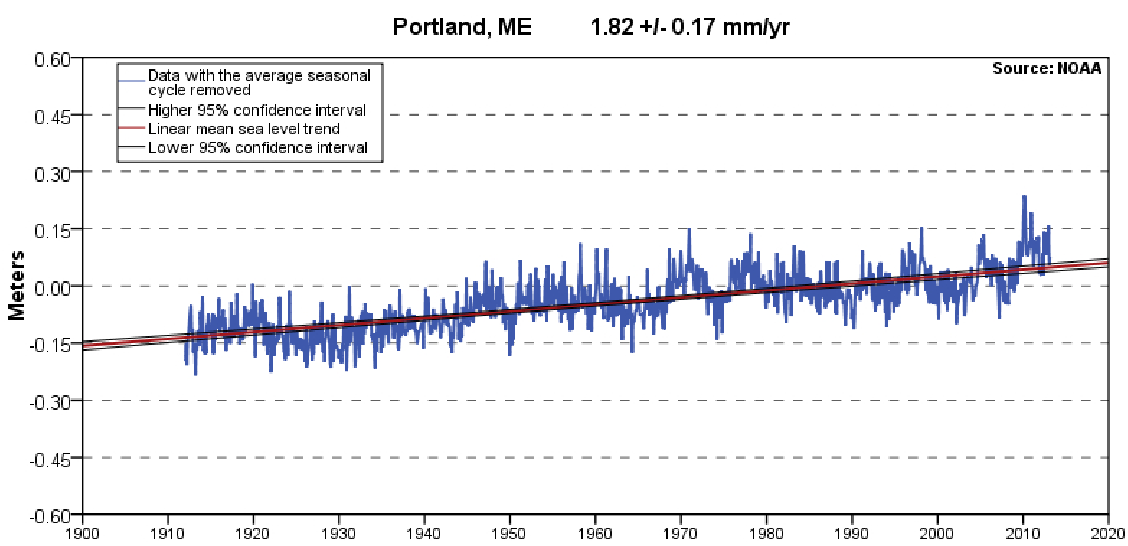


Figure 1.12: Portland, ME, tide gauge documenting trends in local sea level rise since the early 1900's. Local rates of sea level rise are quite consistent with eustatic rates of 1.77 mm +/- .5 mm/yr (IPCC, 2007) (Image modified from Dickson, 2013).

In less than 24 hours, powerful storms are responsible for the same volume of erosion and sediment transport occurring under normal hydrographic conditions throughout a season. Winter storms, commonly known as Nor'easters, have short-period energetic waves that can drastically reduce beach width. In Phippsburg, storm activity has been well documented since the 1600's (Buynevich et al., 2004). The most powerful storms that effect the Maine coastline are Nor'easters (FitzGerald et al., 1989), characterized by their strong northeasterly winds that result from cyclonic low pressure systems gathering in the Gulf of Maine, and thus can sustain powerful winds for long periods of time (Nelson and Fink, 1980). Although other storms do track through Maine, such as southwesterly storms that move in and up the coast (Nelson and Fink, 1980), dissipating in power and erosive potential as they approach the Maine coastline, Nor'easters historically are more significant as they cause intense damage in relatively short periods of time.

In Recent history, high magnitude storms have battered the Maine coastline causing beach erosion, and extensive damages both physically and economically to coastal communities. Historical records document powerful storm activity in Maine as long ago as 1635, when the 'Great Colonial Hurricane' impacted the New England coastline with storm surges reaching over 4m (Buynevich et al., 2004). At the Hunnewell barrier of Popham Beach, buried scarps discovered with ground penetrating radar denote up to 100m of beach loss from a single storm event (Buynevich et al., 2004). Storms of this power are comparable, if not more powerful than modern day storms such as the 'Blizzard of '78', to be discussed shortly, and have recurrence intervals along the century-millennia time frame (Buynevich et al., 2004) Clearly storm activity plays a large role on barrier beach migration along coastal Maine with evidence of massive storm influence found along the Popham - Seawall Barrier complex.

One of the most powerful storms on record is the 'Great Ash Wednesday Storm'. Within only five days, from March 5-9th of 1962, the storm dealt out over three hundred million dollars in property damage along one thousand meters of the Atlantic Coast (Davis et al., 1993, and Davis and Dolan, 1993). The storm had open ocean waves mounting to ten meters high (Dolan and Davis, 1993), average wave heights of 9.1m (Davis and Dolan, 1992) and occurred over several tidal cycles. Therefore the beach systems did not have time to recover, and erosion was irreparable as the storm remained strong for such a long period of time.

For most New Englanders, the 'Blizzard of '78' is considered the coastal storm of record (Marrone, 2008). This Nor'easter was so expansive that storm scarps are still evident to this day in the study zone in Phippsburg, ME, and in many other locations throughout New England. The Nor'easter, from February 6th-8th, 1978, coincided with astronomical spring tides exacerbated the intensity of the storm surge, producing two wave heights over 5meters (Zhang et al., 2001) with average wave height at 10m. The higher than average tides scoured the new England coast line, eroding beach fronts extensively and drastically changing morphologies.

In the 1990's, several strong Nor'easters occurred causing severe damage to coastal New England, and other places along the coast. In 1991, the 'All Hallows' Eve Storm', more commonly referred to as the Perfect Storm, is considered to be the strongest Nor'easter of the past 50 years (Davis and Dolan, 1992). This storm was unique because of the length of time it lasted, over 114 hours from October 28th-31st (Davis and Dolan, 1992, and Davis et al., 1993). On top of that, wave heights reached 10.7m, higher than those during the Ash Wednesday storm, previously considered the most detrimental storm of the age, and sustained wind speeds throughout the duration were between 30 and 40 knots (Davis and Dolan, 1992). The strength of the storm resulted in the destruction of over 100 houses, and over 25 million dollars, only 75 percent of the actual damage costs, in federal spending to repair public transportation and other public facilities (FitzGerald et al., 1994). In 1993, 'The Storm of the Century' or the 1993 Super storm bore down on the Atlantic coast between the Gulf Coast of Florida and Maine, from March 12-14th (Davis and Dolan, 1993, and RMS, 2008). The event caused between 5 and 6 billion dollars in damage through ice, snow, wind, and even tornado damage near the southern extent of the front (RMS, 2008).

The Patriots' Day Storm of April 15th-17th, 2007, a Nor'easter, mostly recognized for the heavy rainfall and extensive flooding the storm evoked, mainly in Massachusetts, Maine, and New Hampshire (Marrone, 2008). Whereas most Nor'easters are characterized by intense and swift snowfalls, this storm produced between 6-8 inches of rainfall in Maine and New Hampshire, and snowfall farther north causing river flooding throughout the storm zone (Douglas and Fairbank, 2011). Hurricane force winds and wave heights reaching 10m generated extensive coastal flooding and erosion, and forced localized regions of New Hampshire and southern Maine to declare a state of emergency (Douglas and Fairbank, 2011).

Hurricane Sandy and the November 7th, 2012 Nor'easter, named the 'Winter Storm Athena' by The Weather Channel occurred during the study period. The Huffington Post (2012) claims that the hurricane claimed 125 lives and cost 62 billion dollars in damage, second to only Hurricane Katrina in 2005. However, severe damage was concentrated along New York and New Jersey, and the storm dissipated by the time it reached most of New England. Within nine days, the Winter Storm Athena struck the Atlantic coast, however major damage was primarily to upper New England. Winter Storm Athena produced sustained 40-60 mph winds and up to two and a half feet of snow fall, sustaining power loss induced by Hurricane Sandy throughout the Northeastern United States (the weather channel). Data from this study can be used to determine the effects of both Sandy and Athena on the barrier beach systems of Phippsburg, ME, as well as compare their effects to historical storms mentioned above.

In order to better quantify storm intensity as well as relate data from one storm event to the next, Dolan and Davis (1992) developed a classification scheme in which storms can be induced by their power. Storm power is a factor of duration and the square of maximum wave height reached during the storm, with a minimum storm threshold wave height of 1.5m (Dolan and Davis, 1992). This index breaks storms up into five categories, ranging from weak to extreme, with increasing power (Dolan and Davis, 1992). The classification scheme is applicable to the storm activity documented in this study, and sets hard parameters defining a storm event.

Chapter II

Methods

(Wescott, 2012)

Field research on the Popham - Seawall beach complex located in Phippsburg, ME, began in the summer of 2012 and extended to the winter of 2013. Research methods included topographic profiling and GPS tracking of morphological features. Field data, maps, satellite imagery, historical photographs, and weather station data were compiled and analyzed back at the Bates College Imaging Center in Lewiston, ME,

2.1 Topographic Profiling

Fourteen transects were surveyed throughout the study period. Survey data were then compiled as plots of elevation change over distance as topographic profiles in Excel and SigmaPlot. Transects are laid out perpendicular to beach front, and consistency from year to year is ensured by locating transects through GPS, especially when transect markers have gone missing.

There are three transects on Ice Box Beach which begin at the bedrock outcrops and extend to the low tide mark, while the two Little Beach transects run from the seawall to the low tide mark (Figure 2.1). Seawall Beach has six transects, all of which start at stakes located along the 78 dune ridge and continue to the low tide mark (Figure 2.1). As of 2010, three new transects on Popham Beach have been surveyed in addition to the established eleven on the Seawall Barrier (Figure 2.2). These transects begin at established benchmarks; the West Bath House, a stake along tree line, and the top of the East stair case, and run to low tide mark accordingly. Azimuths are used at all transects and consistency is ensured based off of compass bearings taken and recorded at each transect.

Figure 2.1: Transect Location map for all transects on the Seawall Barrier as well as on Pocket Beaches (Schuler, 2010).

Figure 2.2: Location map of Popham Transects shown in Pink. Clockwise from left is West Bath House, Popham Middle, and East Stair Transects. Transects have been surveyed since 2010 (BCIC, 2013).

Profiles were conducted using both the Emory method and the Auto Level method. The Emory method is a cumulative method in which the horizon is utilized to determine change along the beach slope (Figure 2.3). Two sticks are attached by string and marked in cm increments from top to bottom. An initial measurement is taken at the beginning of each transect by pulling sticks apart until the string attaching them goes taut. The sticks are then moved along a measuring tape laid out from the back dune markers to the low tide mark, pulling the string between taut over specific increments of distance between each measurement location. Change is cumulative as the sticks migrate down transect in specific increments. In sections with drastic change such as the berm, one meter increments are employed, whereas longer increments such as three and six meters are used when sections experience more gradual slope change. Eventually elevation change can be imported into Microsoft excel or SigmaPlot and formulated into a profile which demonstrates slope changes along the transect.

The second method utilized to survey the beaches is the Auto Level method. This method was used in all survey periods other than the June period. Profiles were documented by placing the auto level telescope mechanism at each benchmark denoting the beginning of transects, and laying out a measuring tape from the bench mark along the transects (figure 2.4). An initial height measurement was taken with a stadia rod. Once this initial measurement was taken, the stadia rod was marched down transect in specific increments of distance, in which areas of drastic change were surveyed over smaller increments and areas of gradual change were surveyed over larger increments. The auto level remains stationary, and a cross hair within the telescope intersects the stadia rod. This intersection was recorded, as

Figure 2.3: Margaret Pickoff holding Emory sticks while completing the Emory surveying method on Seawall Beach, summer of 2012. Emory method was only used in June (Wescott, 2012).

Figure 2.4: Amanda Wescott completing Auto Level surveys on Seawall Beach, fall of 2012. All but the June round of profiling was completed using the Auto Level method (Wescott, 2012).

well as the distance down transect at which each measurement was taken. This process was repeated until the transects were completed. Often visibility through the auto level became unclear as the stadia rod moved long distances from the bench mark. When this happened the auto level was relocated on the beach face, a new initial eye height measurement taken, and surveying continued from the previous measurement. Back in the lab, data was processed using Excel and SigmaPlot, in which varied instrument heights were accounted for in order to generate a topographic profile of the slope change along transect.

2.2 GPS Tracking

High resolution GPS systems were utilized when recording transect bench marks and to track morphological changes along the Sprague River inlet, Morse River inlet, and the frontal dune ridges along both beach complexes. Transect bench mark location were documented using a Garmin eTrex unit (figure 2.5), and way points were then uploaded and embedded into the 2012 orthographic image of the field site using ArcMap. Trimble high resolution systems were used to track migration of both the Sprague and Morse River inlets and the frontal dune ridges during the summer and fall seasons (figure 2.6). Dune ridge location was tracked during August, October, and November of 2012, and the inlets were tracked in August and December of 2012. These tracks were embedded into the 2011 orthographic image of the field site using ArcMap, to demonstrate migration on an annual as well as seasonal scale.

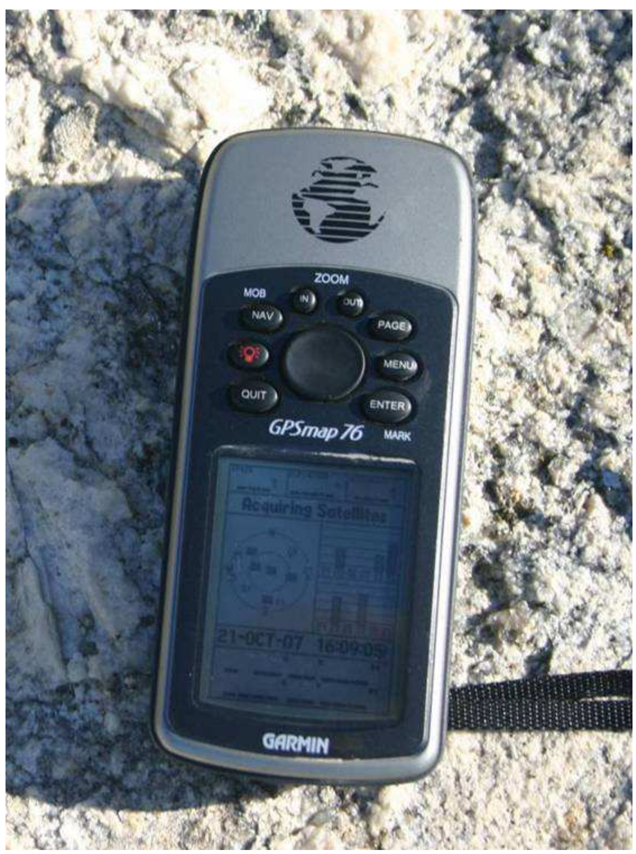


Figure 2.5: Garmin Etrex handheld unit used to document benchmark locations (Schuler, 2010).

Figure 2.6: Trimble high resolution GPS system. Used in study to track morphological changes of the frontal dune ridge and the Sprague and Morse migratory inlets (Russo, 2013).

2.3 Weather Station Analysis

Weather data was made readily available from the National Data Buoy Center via the NOAA website. Data was selected from Buoy 44007 in Casco Bay located only 12 nautical miles southeast off the coast of Portland, ME, where weather activity reflects conditions characteristic of the study zone (NOAA, 2013). Buoy 44007 (Figure 2.7) records wind direction and speed, gust speed, wave height, mean wave direction and period, air and water temperatures, barometric pressure and dew point each hour (figure). Recorded data were downloaded for the study period encompassing June 2012 - December 2012, and plotted using Microsoft Excel. Graphically represented data, when compared to profiles and GPS data, underscores the extent of which storm activity has on forcing morphological changes on the beach complexes.

Figure 2.7: NDBC weather Buoy 44007 located southeast off the coast of Portland, ME in Casco Bay. Weather data recorded from buoy was downloaded and compared to profile data (NOAA, 2013).

Michael Retelle installed a weather station on the flag pole located in the parking lot at Popham Beach state park in 2010 (Figure 2.8). The station, which was operative until just recently when irreparable damage to wind direction and wind speed sensors occurred during a storm. The station was sheared from the top of the flag pole, will not be replaced until spring of 2013, and thus the NOAA weather station buoys are the sole source of weather data during the study period.

The weather data downloaded from buoy 44007 can be analyzed using classification schemes developed by Dolan and Davis (1992, 1993). An intensity scale for Nor'easters from weak to extreme classes based on a wave "power-index" was developed by multiplying the specific storm's duration by the square of the maximum wave height, and storms indexed through this classification scheme (Dolan and Davis, 1993). Although Dolan and Davis (1993) only categorized storms up until 1992, the classification process can be applied to recent storms, such as Hurricane Sandy and the Nor'easters of November 7th, 2012, both of which affected the field site.

Figure 2.8): Weather station (left) installed at the Popham Beach flag pole (right) located in the parking lot near the West Bath house. (Retelle, 2010).

2.4 Historical Comparisons of Data and Images

Emily Chandler (2009) collected over 100 historical images and maps from the Small Point community to track the southwestern spit of Seawall beach related to the migration of the Sprague River inlet. Since 2009, more images have been donated by members of the community, and photographs taken by student researchers and geology classes have been added to the collection.

Satellite imagery and other aerial photographs were obtained through the Bates College Imaging Center from as far back as 1953 up to 2012. Aerial imagery has since been georeferenced using ArcMap, and can be used comparatively to show changes throughout the beach complexes.

Reliable profile and GPS data has been consistently collected by senior thesis researchers since 2008, and can be stacked with data collected during this study period to graphically represent the changes occurring at the Popham - Seawall barrier beach complexes. Data for Popham Beach has only been collected since summer of 2010, data on Seawall beach since 2008, and data for the two pocket beaches has been recorded since summer 2009.

Chapter III
Results

(Wescott, 2012)

3.1 Weather Data and Storm Events

Diagrams 3.1a-d depict both weather and storm activity influencing the barrier system morphology. Wave direction was not recorded by NDBC Buoy 44007 nor by nearby buoys, therefore it has been omitted from data sets. In general, weather activity associated with the study zone show consistent increase of severity, beginning with calmer conditions during the summer season to more active and severe conditions in the late fall and winter seasons.

Figure 3.1a illustrates this trend of increasing weather activity. During the summer season, June 2012 through August 2012, wind speeds averaged 3.8 m/s with a maximum

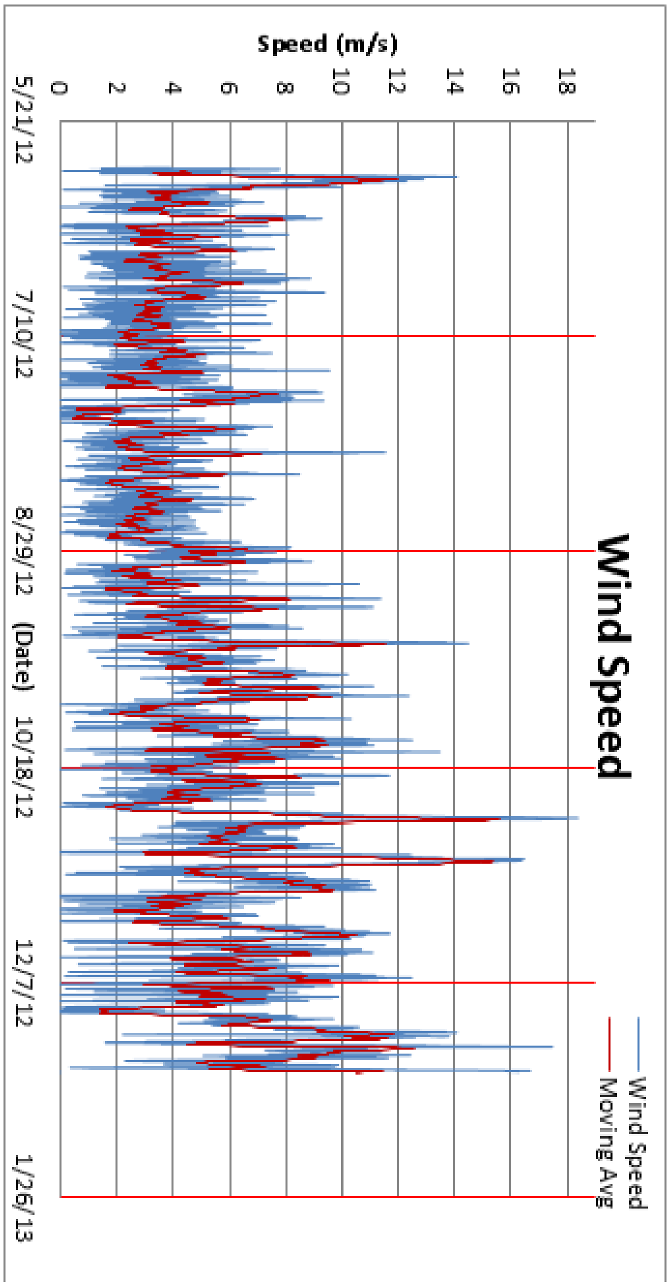


Figure 3.1a: Wind Speeds (m/s)from buoy 44007 from June 1st- December 31st of 2012

recorded at 14.1 m/s during a storm event in the beginning of the month of June, before profile measurements commenced. Wind speeds increased in the fall period of September-November 2012 to an average of 5.6 m/s. The maximum wind speed recorded during the entire study period occurred during Hurricane Sandy on October 29th, 2012, and registered at 18.4 m/s. Average wind speeds continued to increase into the late fall period of October-December, with averages reaching 6.8 m/s, with a seasonal maximum wind speed of 17.5 m/s.

Wind direction recorded (Figure 3.1b) during the summer period averaged at 191 degrees. These southern winds continued into the fall period which had average wind directions of 181 degrees. Quite similarly average wind direction for the late fall period was 180 degrees, pre- dominantly southern winds denoting calm conditions. It is important to note that as an overall trend, wind speeds originated in the south during the summer period, but as the year

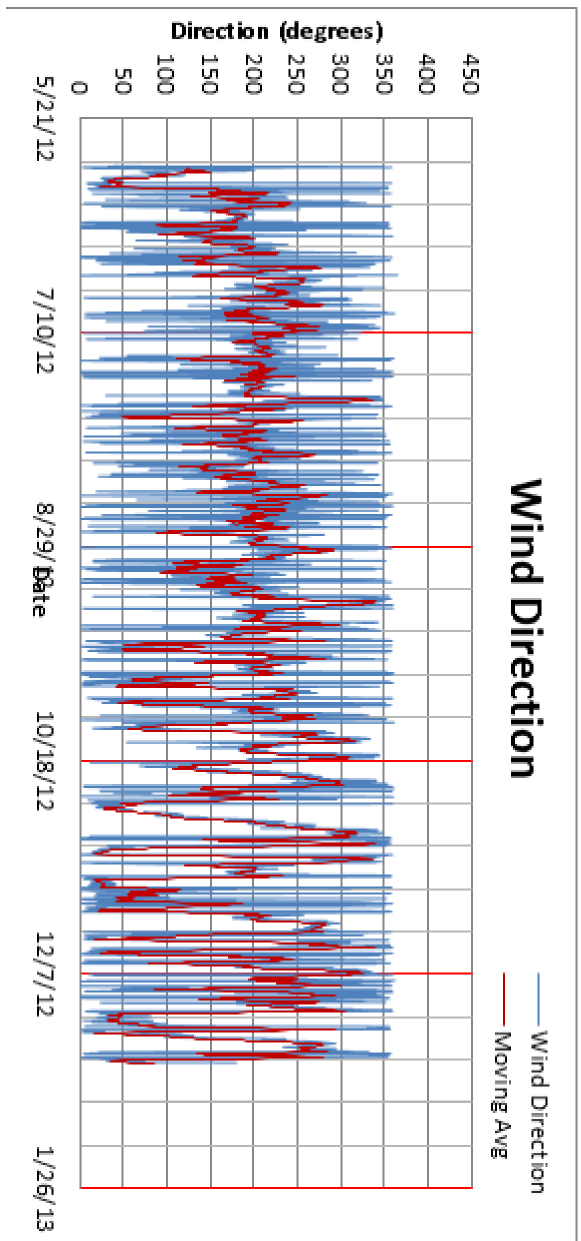


Figure 3.1b: Wind direction (degrees) from buoy 44007 from June 1st - December 31st of 2012

progressed wind direction originated predominately from the north to northeast, as recorded by buoy 44007.

Figure 3.1c shows wave height trends throughout the entire study period. During the summer, seas were quite calm with average deep sea wave heights of .69m, and a maximum wave height of 3.5 meters. In the early fall period average wave heights increased to 1.02m, while the maximum deep sea wave height registered at 7.11m. Deep sea wave heights for the late fall period averaged at 1.38m. During December the maximum wave height was recorded at 8.12m, however profile data does not extend into the winter season, and does not reflect the effects of wave forcing during December. Figure 3.1c denotes wave height trends consistent with meteorological trends of the region in which wave heights are lesser during summer months and consistently increase throughout the fall and winter seasons.

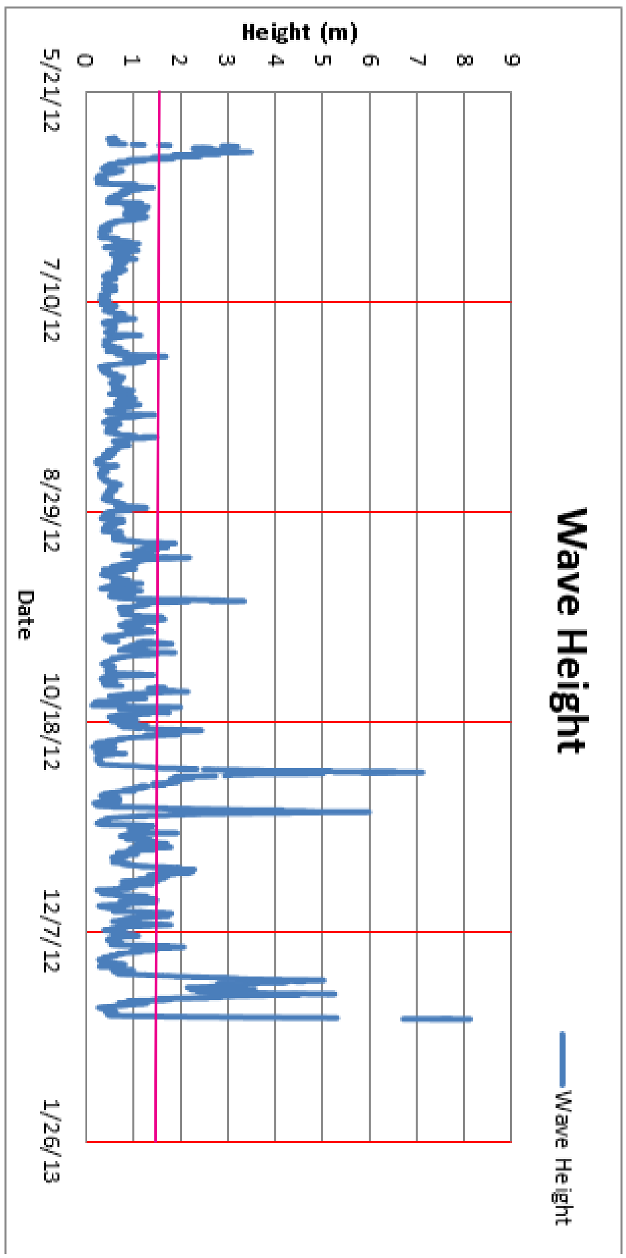


Figure 3.1c: Wave height (m) from Buoy 44007 from June 1st, 2012- December 31st, 2012

Wave height values are directly related to storm classification based on the Dolan and Davis (1992) storm classification scheme. This scale categorizes storms into five classes based on deep sea wave heights of at least 1.5 meters or higher. Using this classification scheme storm activity was documented as seen in Table 3.1.

Date	Duration (hrs)	Max wave Ht (m)	Power (m^2*h)	Class	Average Wind speed (m/s)	Average Wind Direction (^{o})	Ave Wave ht (m)	Lunar Cycle
2-Jun	81	3.5	992.25	severe	8.65	60.79	3.64	Spring
8-Jun	8	2.19	38.37	weak	8.08	201.44	1.82	Neap
18-Jun	20	3.33	221.78	significant	10.61	195.65	2.43	Spring
23-Sep	8	1.66	22.04	weak	5.97	239.93	1.47	Neap
29-Sep	9	1.81	29.48	weak	9.92	26.00	1.66	Spring
1-Oct	7	1.87	24.48	weak	10.64	236.29	1.71	
9-Oct	1	1.66	2.76	weak	7.80	76.00	1.66	
10-Oct	19	2.16	88.65	moderate	6.67	103.32	1.70	
14-Oct	4	2	16.00	weak	11.25	221.50	1.79	Spring
15-Oct	7	1.75	21.44	weak	9.10	189.43	1.64	
19-Oct	33	2.44	196.47	significant	6.12	175.26	1.85	Neap
28-Oct	**101**	**7.11**	**5105.76**	**extreme**	**8.69**	**133.48**	**2.58**	**Spring**
7-Nov	**42**	**5.97**	**1496.92**	**severe**	**13.90**	**74.40**	**3.13**	**Neap**
13-Nov	4	1.92	14.75	weak	9.30	203.00	1.71	Spring
15-Nov	7	1.79	22.43	weak	4.92	29.40	1.66	
21-Nov	66	2.3	349.14	significant	5.13	164.95	1.77	Neap
2-Dec	20	1.8	64.80	weak	6.17	226.71	1.65	
5-Dec	8	1.79	25.63	weak	9.10	207.22	1.63	Neap
10-Dec	11	2.08	47.59	weak	1.82	215.17	1.82	Spring
17-Dec	137	5.14	3619.49	extreme	9.58	140.04	3.75	Neap
27-Dec	15	8.12	989.02	severe	16.11	95.31	4.74	Spring

Table 3.1: Classification scheme of storms from June 1st, 2012 - December 31st, 2012 based on parameters defined by Dolan and Davis (1992). Storm Power is a factor of duration (hrs) and max wave height (m). Note Hurricane Sandy and the Winter Storm Athena, October 28th and November 7th, respectively, two of the most powerful storms to befall land during the study period.

According to the National Weather Service (2013) hurricane season lasts from June 1st through November 30th. Over 97% of tropical storm activity occurs within this time frame with the bulk of activity confined to the Months of August, September and October (Dorst, 2010). For the Atlantic Basin, and thus the Maine coast, September characteristically contains most of this storm activity (Dorst, 2010). However, frequent storms are documented in the months of December and May as well (Dorst, 2010).

Twenty storms took place during the study period. A severe storm on the 2nd of June and a significant storm on the 18th of June occurred before profiling commenced. An extreme storm on the 17th of December and a severe storm on the 27th of December occurred after field work was completed. These two storms breached land outside of the defined parameters of hurricane season, but all aforementioned events were included in results for comparison with storms within the study period.

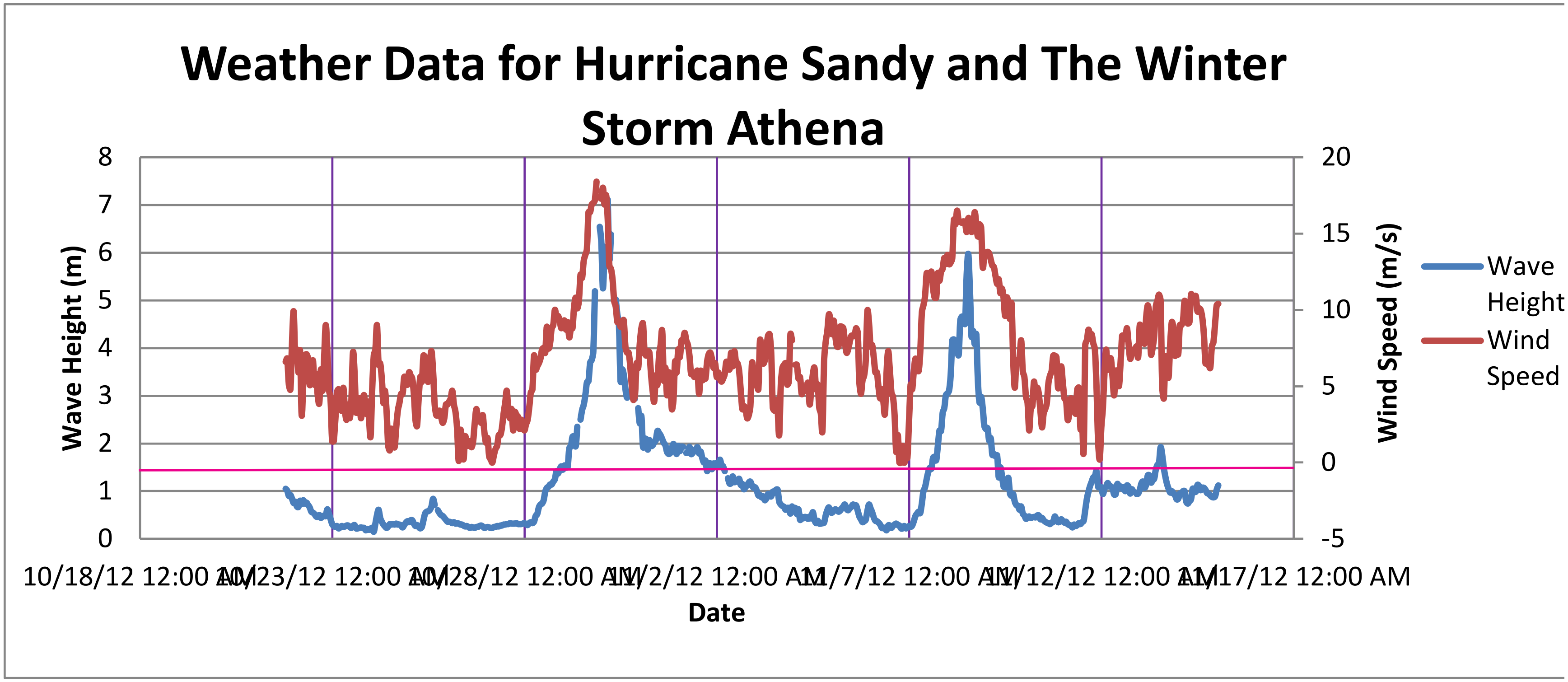


Figure 3.1d: Composite graph of wave height (m) and wind speeds (m/s) for Hurricane Sandy and the winter storm Athena. Pink line denotes storm threshold (Dolan and Davis 1992) . Note contrast of storm conditions to fair weather conditions before and after each specific storm event.

Of the 20 documented storms only two were classified as extreme, two as severe, three as significant, and one as moderate. The remaining twelve storms were classified as weak impacting storms on the Maine coast. Similar to trends described previously by Dorst (2010), Phippsburg primarily experienced all major storm activity during the months of September, October, and November. Two of the more powerful storms were Hurricane Sandy and Winter Storm Athena, which occurred on the 28th of October and the 7th of November. Hurricane Sandy was a category five storm as defined by the Dolan and Davis (1992) scheme, and lasted a total of 101 hours with a storm power of 5105.76, a product of the storm duration and max wave height. It is important to note that the storm was considered a 'weak' hurricane, but coincided with Spring tides, thus magnifying storm intensity and resulting damages. Winter storm Athena lasted 42 hours and had a storm power of 1496.92. These two storms had major impacts on the Maine coast in terms of sand transportation and beach loss, specifically in this study zone. Figure 3.1d delineates wind and wave height conditions which encompass both storm events, as well as the calm weather conditions before and after Sandy and Athena.

Although winter storm Athena had max wave heights 5.97 m, average wave heights of 3.11 m, and average wind speeds of 13.90 m/s, which are quite similar to Hurricane Sandy's max wave height of 7.11 m, average wave heights of only 2.58m, and average wind speeds of only 8.69 m/s, Winter storm Athena was not nearly as powerful as Hurricane Sandy because of its shorter duration, and landfall during neap tides (Table 3.1).

3.2 Topographic Profiles and Weather Data

Topographic profiles were surveyed from June 28th through November 18th, 2012 along 14 transects throughout the Popham-Seawall complex. Comparison of profile data are categorized by season. Summer profiles include June 28th - August 22nd, 2012, early fall profiles from August 22nd - October 16th, 2012, and late fall profiles October 16th - November 18th, 2012. Late fall profiles specifically document changes inflicted by Hurricane Sandy and The Winter Storm Athena.

3.2.1 Summer Profiles and Weather Data

Summer profiles are presented in figures 3.2a - 3.2n. Summer data shows overall erosive trends from the beach front at all transect locations excluding W500, Little Beach I, Ice Box I, II, III, and Popham West Bath House (Figures 3.2d, g, i-k, and l). Transects E200 and E100 show accretion near the frontal dune ridge; however along the length of the profile the beach tends to erode from the first profile in June, to the final profile in August (Figure 3.2a-b). Transects W100 and W1100 show erosion at the frontal dune ridge and illustrate the recession of the ridge landward (Figure 3.2c, and 3.2e) while at station W500 (Figure 3.2d) there was little to no change throughout the summer. Profiles resemble erosional profiles rather than expected constructional profile models (Nelson and Fink, 1980) with very limited berm features. W1500 (figure 3.2f) shows continued erosion as sand migrates long shore, eventually accumulating on the western portion of the southern Seawall Beach spit.

Profile comparison for Little Beach I (Figure 3.2g) and Little Beach II (3.2h) illustrate accretion of sand to the shore face, reinforcing migration of the southern spit of Seawall Beach west towards the Cape Small headland. Although Little Beach II does show this same sand accretion from the July to August profiles, there was significant erosion on the entirety of the beach front from the June-July profiles at this location (Figure 3.2h).

Ice Box Beach I (3.2i) experienced accretion along the shore face including continued buildup of the berm throughout the summer. Ice Box Beach II (3.2j) underwent overall accretion along the shore face as the summer progressed, however there was minor erosion near the headland at this location. Ice Box Beach III (Figure 3.2k) exhibits minor accretion throughout the summer with what seems to be welding of an off shore sand source to the low tide terrace of the pocket beach. There was minor erosion from the July to August profiles.

The profiles of Popham Beach show less overall consistency than do those from Little Beach and Ice Box Beach. The West Bath House profiles show accretion plausibly by the welding of an off shore bar from June to July, and almost no change from July to August (Figure 3.2l). Popham Middle (Figure 3.2m) demonstrates intense erosion from June to July. However as the season progressed, accretion within the tidal pool and along the low tide terrace is visible, but there is little change other than slight accretion from July to August. Profile comparison from the East Stair transect (Figure 3.2n) shows limited change between the June and August profiles, however accretion occurred along the berm from June to July, but this accumulation was lost by August. This section of the beach has a steep transition from the frontal dune ridge to the berm and into the shore face, and is highly susceptible to erosion as the dune face falls onto the berm and is washed away with tides. Weather data corresponding to the summer season are presented in Figures 3.3a-c.

As expected, wind speeds for the summer months of June through August were quite low, averaging 3.81 m/s originating primarily from the south. Although wind speeds were calm, wave heights averaged at about .69m for the period, a relatively high average as the wave height storm threshold is 1.5 m as dictated by Dolan and Davis (1992). Wave heights did not cross the storm threshold more than 3 times in the summer season, with a severe, weak, and a significant storm impacting the coastline during the month of June. The most powerful storm of the season was the severe storm on the 2nd of June, with a total power of 992.25 over an 81 hour duration period. During this storm the maximum wave height for the entire season was reached at 3.5m. This specific storm coincided with an astronomical spring high tide; however wave heights were not large enough nor were wind speeds strong enough to cause excessive erosion at the study zone.

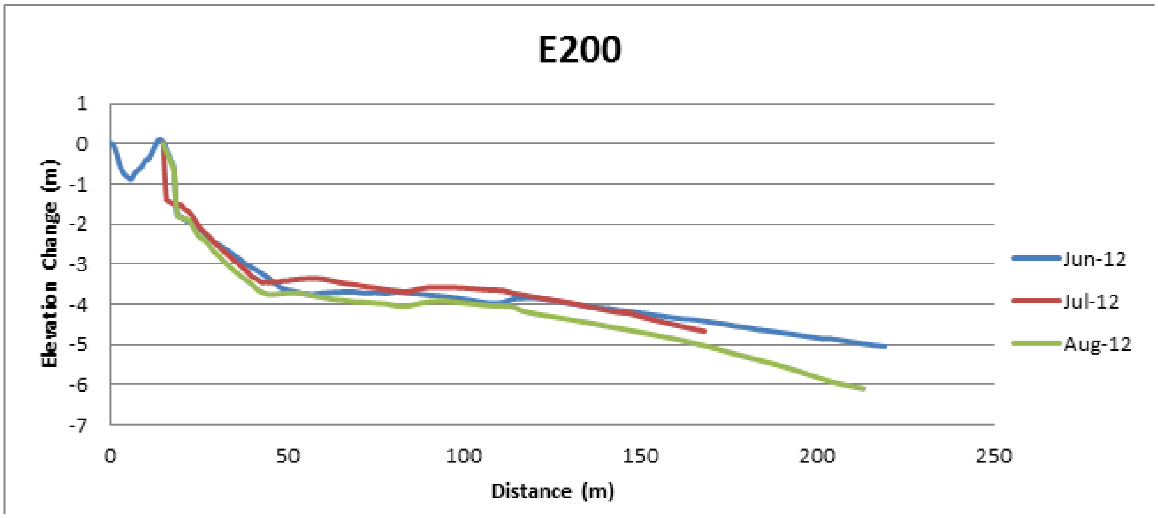


Figure 3.2a: Topographic profile results for E200 during the summer period in 2012

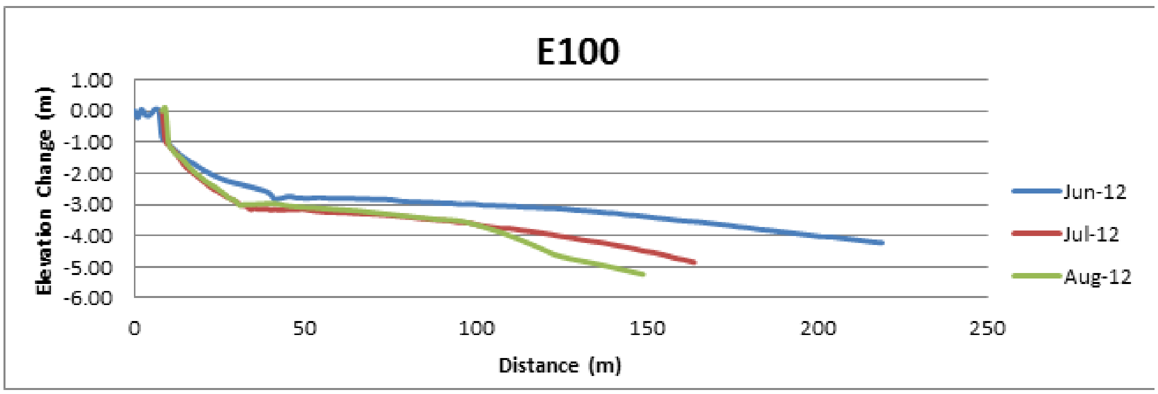


Figure 3.2b: Topographic profile results for E100 during the summer period in 2012.

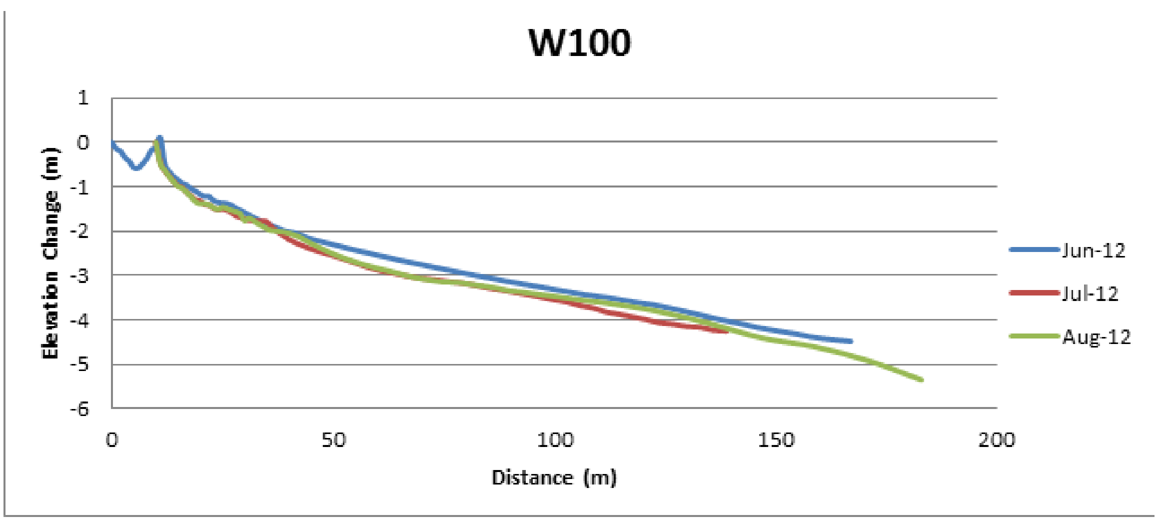


Figure 3.2c: Topographic profile results for W100 during the summer period in 2012.

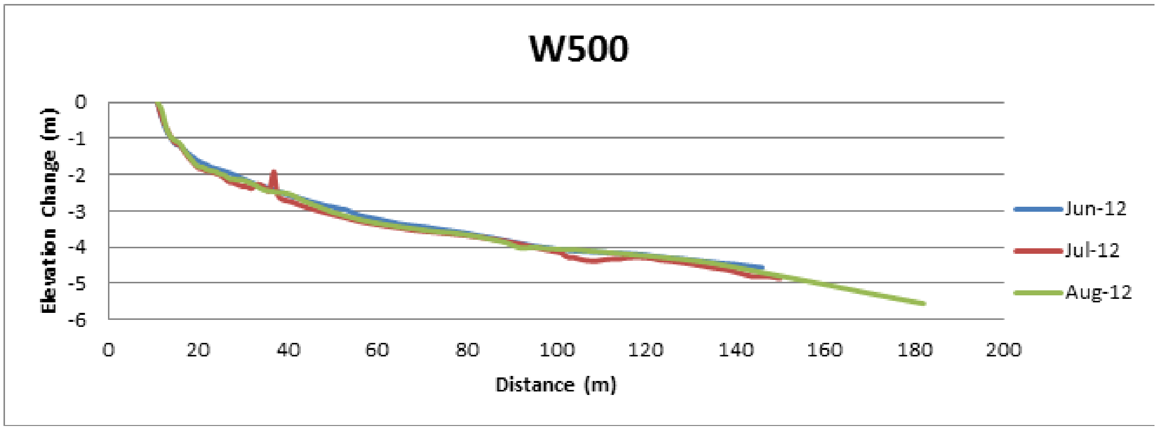


Figure 3.2d: Topographic profile results for W500 during the summer period in 2012.

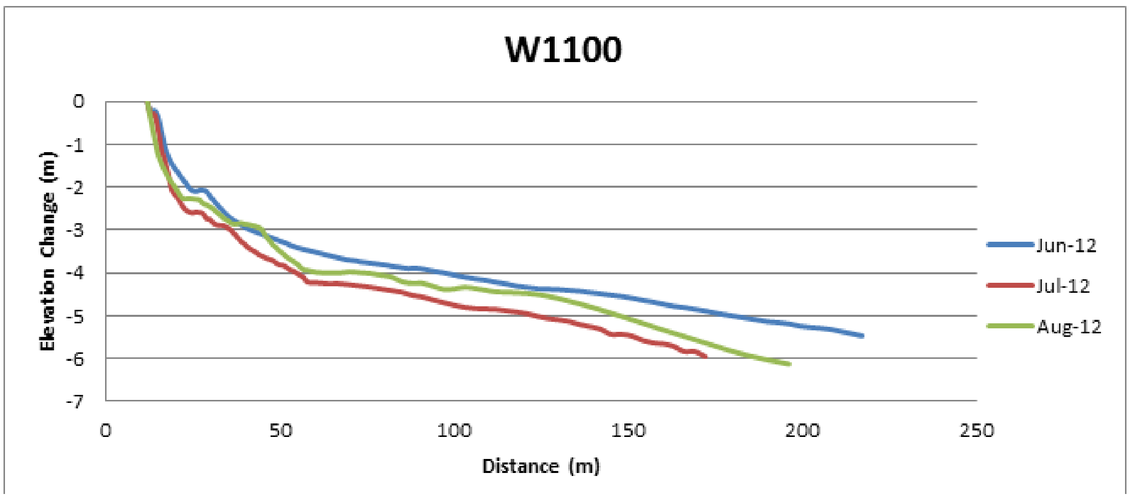


Figure 3.2e: Topographic profile results for W1100 during the summer period in 2012.

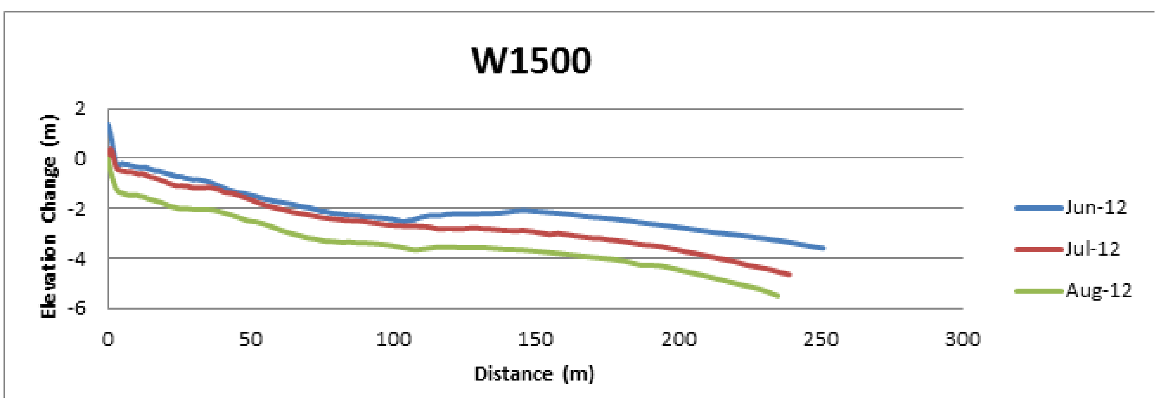


Figure 3.2f: Topographic profile results for W1500 during the summer period in 2012.

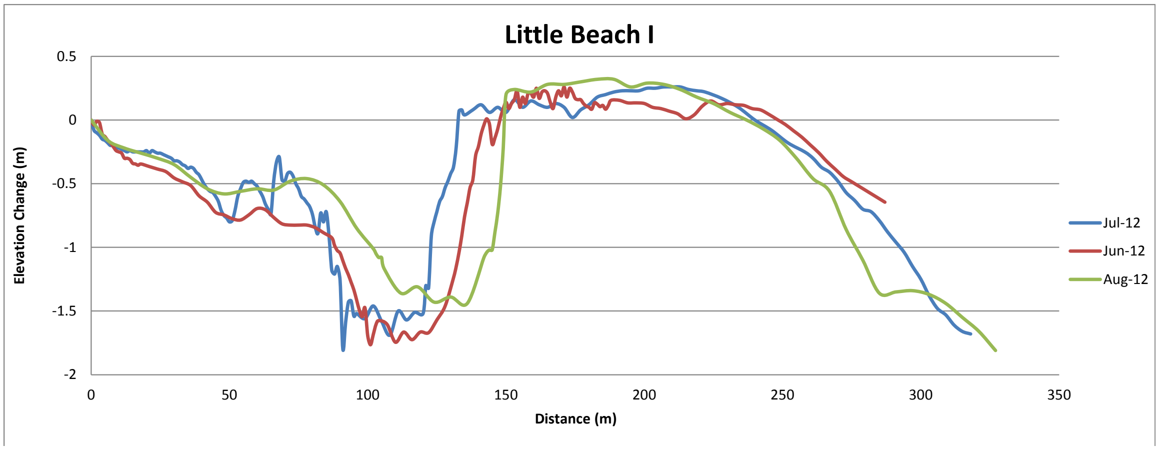


Figure 3.2g: Topographic profile results for Little Beach I during the summer period in 2012.

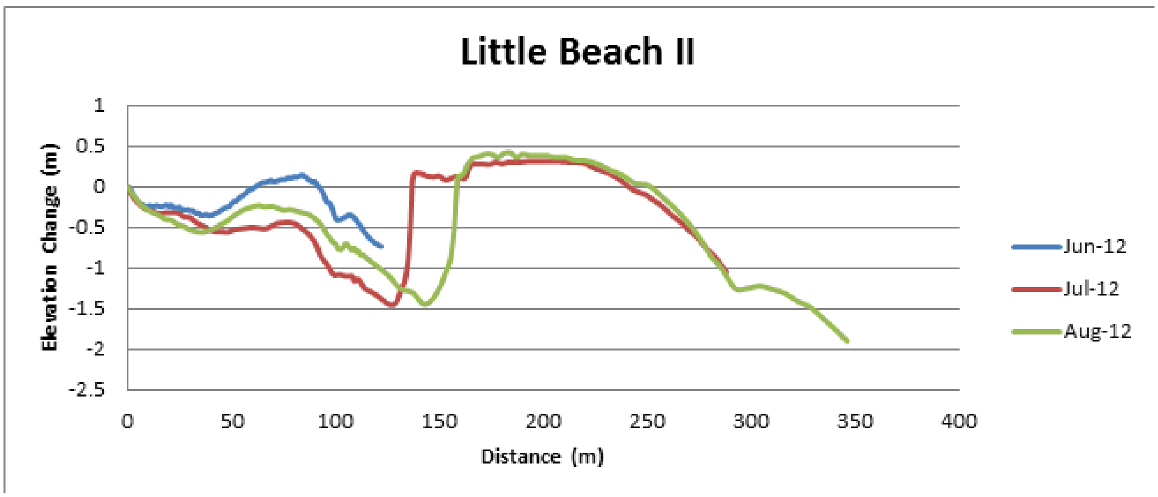


Figure 3.2h: Topographic profile results for Little Beach II during the summer period in 2012.

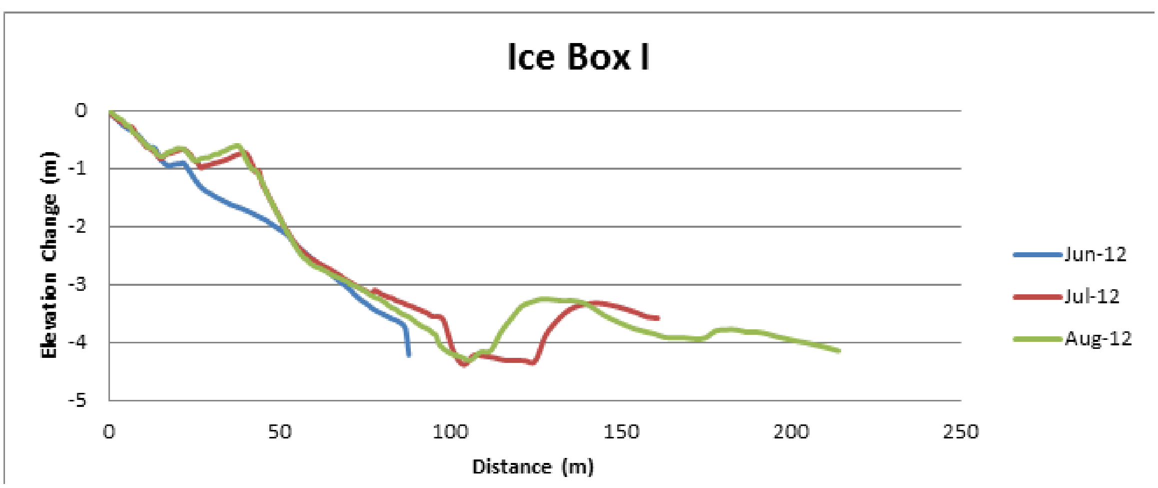


Figure 3.2i: Topographic profile results for Ice Box I during the summer period in 2012.

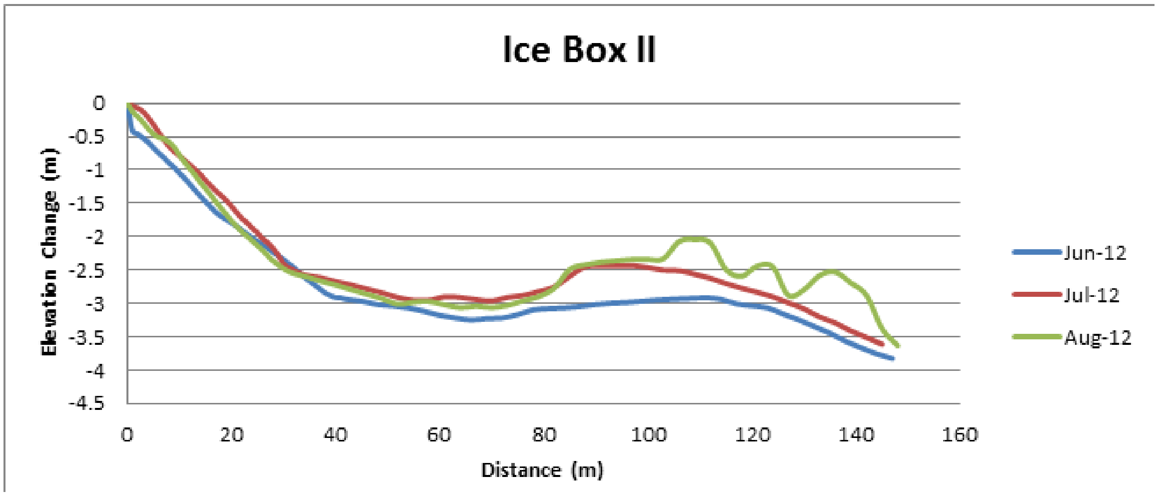


Figure 3.2j: Topographic profile results for Ice Box II during the summer period in 2012.

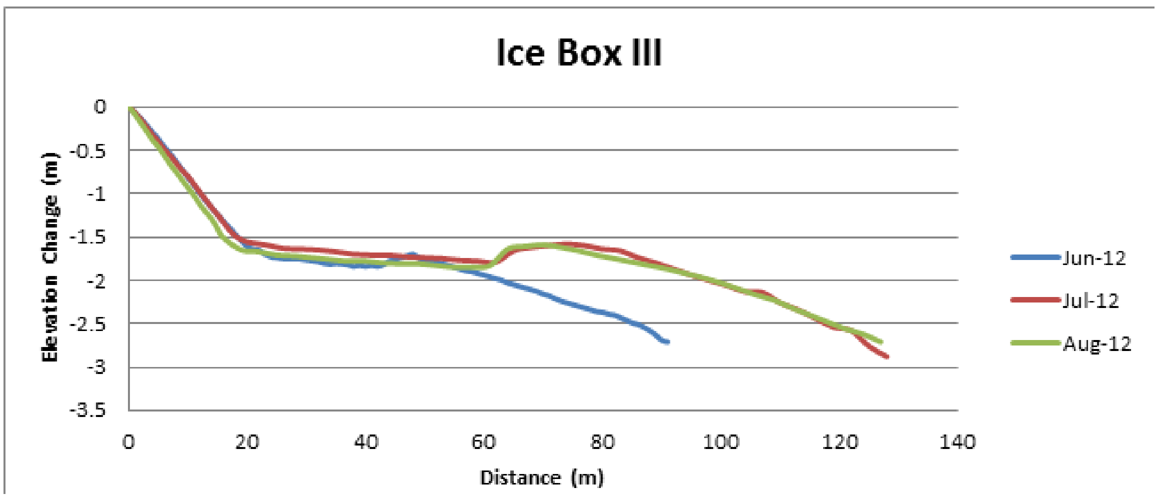


Figure 3.2k: Topographic profile results for Ice Box III during the summer period in 2012.

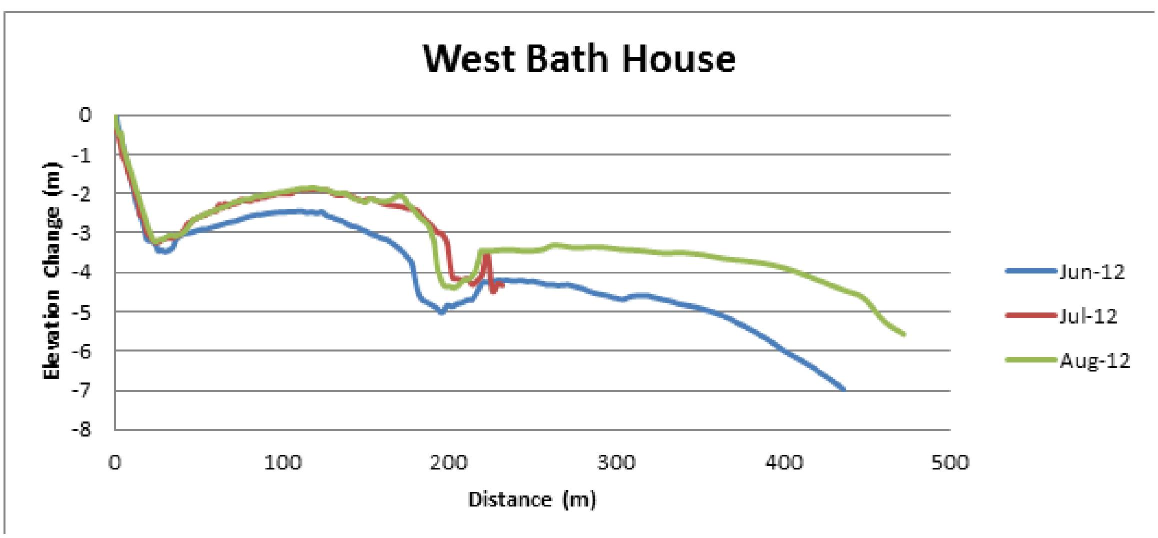


Figure 3.2l: Topographic profile results for West Bath house during the summer period in 2012.

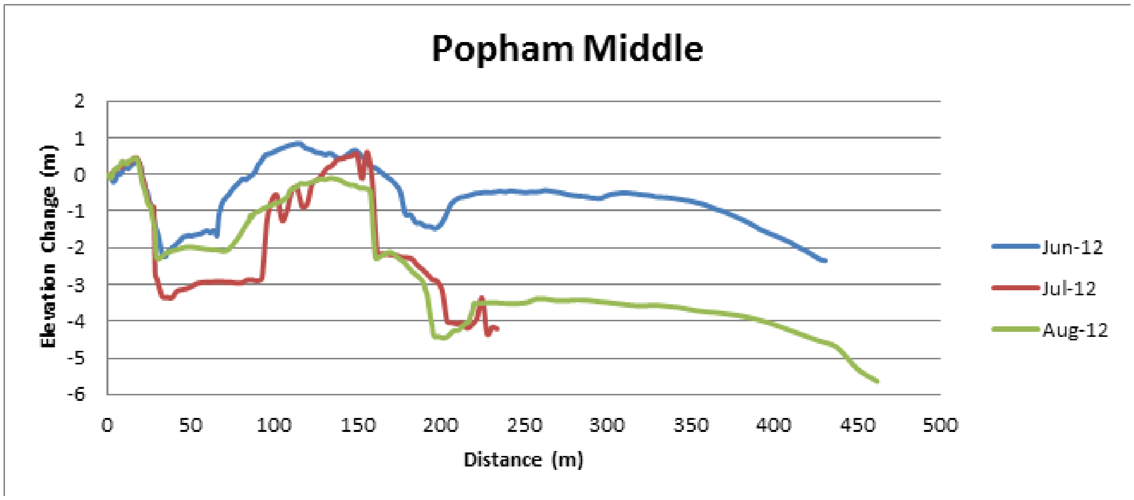


Figure 3.2m: Topographic profile results for Popham Middle during the summer period in 2012.

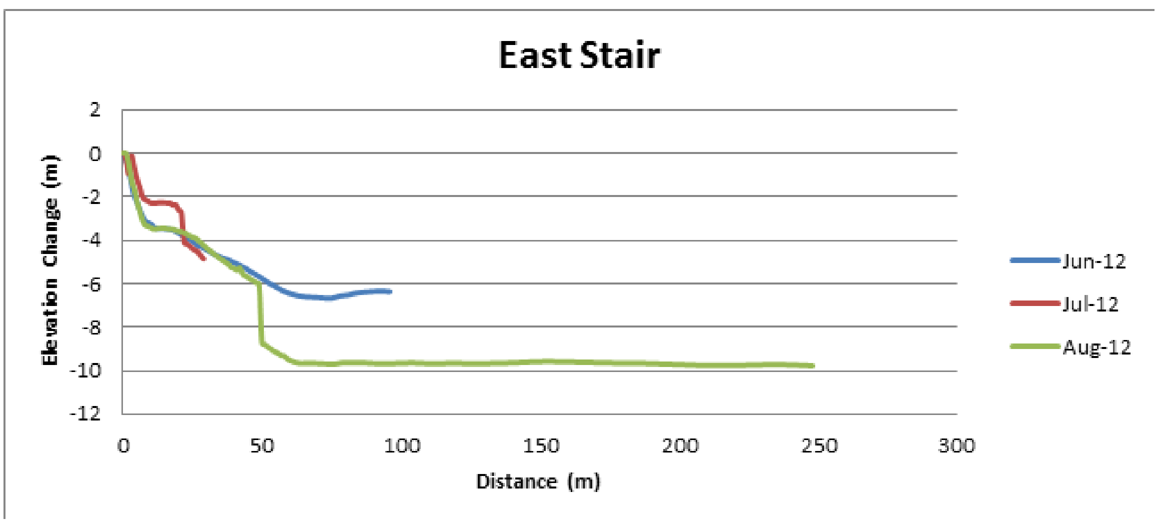


Figure 3.2n: Topographic profile results for East Stair during the summer period in 2012.

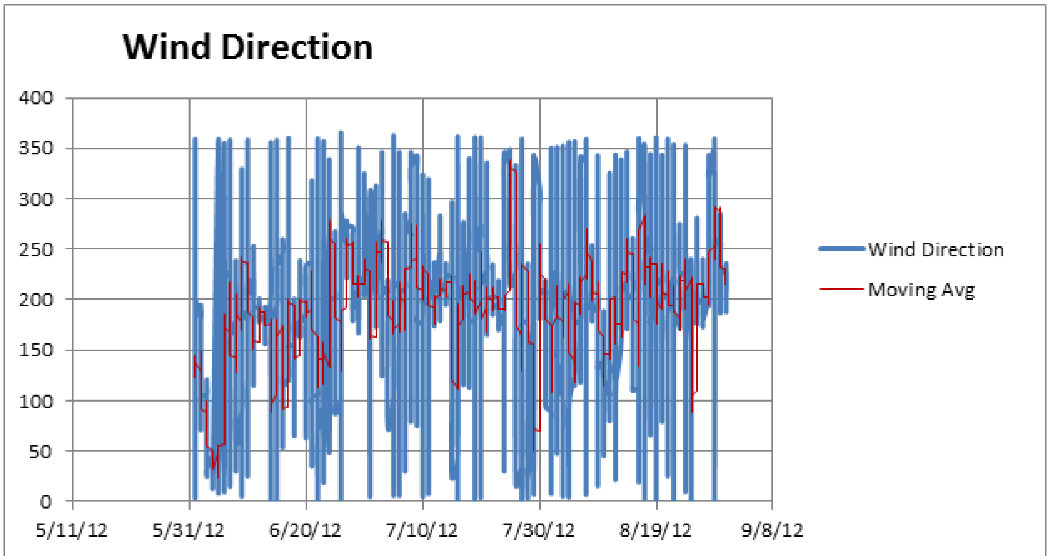


Figure 3.3a: Wind direction (degrees) from Buoy 44007 from June 1st-August 31st of 2012

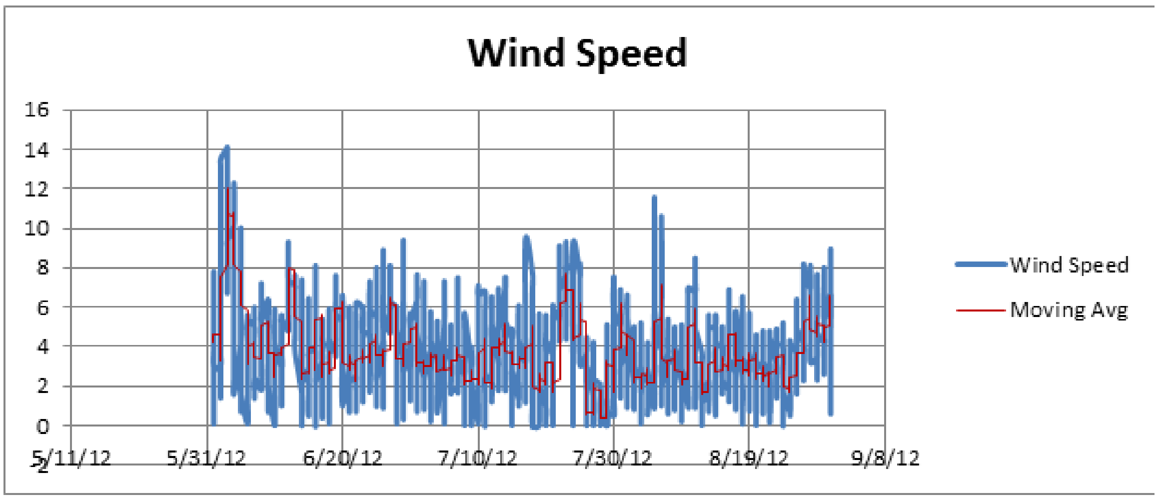


Figure 3.3b: Wind speed (m/s) from Buoy 44007 from June 1st-August 31st of 2012

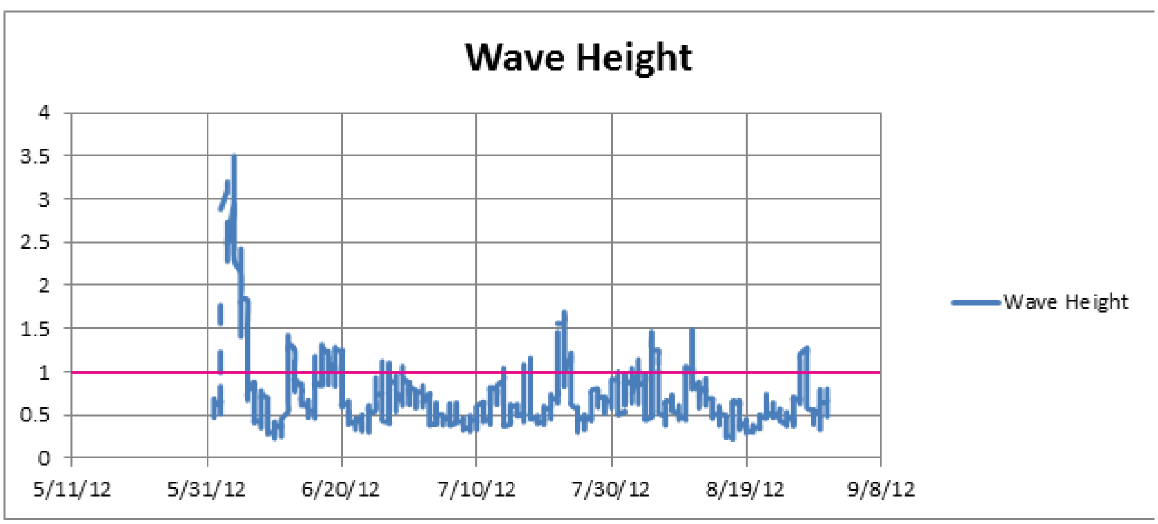


Figure 3.3c: Wave height (m) from Buooy 44007 from June 1st-August 31st of 2012

3.2.2 Early Fall Profiles and Weather Data

Profile comparison from August 18th through October 28th of 2012 is described by figures 3.4a-n, and shows various trends of sand migration throughout the Popham - Seawall complex. Profiles E200 and W100 experienced erosion of respective berm features, while E100 (Figure 3.4b) experienced accretion and growth of the berm feature. W500, W1100, and W1500 experienced no change at the berm.

As summer turns into fall and storm activity, wind speeds, and wave heights increase, amplified erosion and development of erosional profiles (Nelson and Fink, 1980) is expected and quite characteristic of these early fall profiles. Disregarding berm activity, transects at W100, W1500, W1100, and E100 experience erosion past the plunge step, with profile W1100 (Figure 3.4e) containing the majority of smoothing along the beach face. Profiles E200 (Figure 3.4a) and W500 (Figure 3.4d) are the only two profiles along the Seawall Barrier which experienced accretion along the shore face, which can be both attributed to migration of the Morse Channel northward and away from profile E200, and wave corridor action allowing continued welding of off shore sand bars onto the terrace near W500.

The two pocket beaches separated from the main Seawall Barrier by the Sprague River Channel, Little Beach and Ice Box Beach show overall erosion occurring at all transects. Little Beach I and II (Figures 3.4g-h) exhibit migration of the Sprague River Channel in a south to southwestern direction towards the Cape Small headland, causing erosion along the recreational beach and along the southern spit of Seawall beach. It is important to note that despite this migration and associated erosion to the beach face, Little Beach I does exhibit slight accretion near the constructed seawall. Ice Box I, II, and III (Figures 3.4i-k) all show accretion to the recreation beach face. In Ice Box I and III sand migrates landward, up the beach face in a westerly direction. Ice Box III experiences higher rates of described migration than Ice Box I, where accretion is limited to beach front directly at the base of the Cape Small headland rather than along the entire transect. Ice Box II shows large amounts of accretion which enhances a ridge-runnel topographic feature, about 40m away from the headland base. The development of the runnel feature is also visible at Ice Box III, however the runnel is located only 20m away from the headland at this transect.

Figures 3.4l-n represent profiles of the West Bath House, Popham Middle, and the East Stair, respectively. Profile comparison shows almost no change at the West Bath House, however slight erosion and a resulting western, landward migration of the old Morse River Channel is visible. Popham Middle and the East Stair both exhibit obvious accretion to the beach face, with the majority of accretion occurring past the plunge step at the East Stair transect. Popham Middle shows erosion of the recreational beach face in an easterly direction as the old Morse Channel mouth continues to migrate seaward, allowing for the accretion visible on the ridge and runnel system of the beach face in figure 3.4m. The Popham barrier experiences less smoothing of constructional, summer, beach features than does the Seawall barrier.

Weather data corresponding to this period is represented by figures 3.5a-c. Overall, data reflects the transition of calm summer conditions to more intense storm conditions characteristic of hurricane season. Wind speeds increased from 3.81 m/s to 5.66 m/s on average, although overall wind direction still originates from a southern source. During storm conditions however, winds tend to originate from a northeasterly direction, approximately 61 degrees. Max wind speeds for the period reached 18.4 m/s during Hurricane Sandy, a severe category storm with a duration of 101 hours and total power of 5105.76 (Table 1). The hurricane commenced on October 29th, near the end of this period, and continued until November 2nd, which is reflected in both weather data and profile comparison for the late fall period. On average the hurricane maintained wind speeds of about 8.69 m/s, significantly greater than overall average speeds for both late fall and summer seasons. Wave heights for Hurricane Sandy reached 7.11m, and coincidently were the maximum wave heights recorded during the early fall period. Once again, this is significantly higher than the average wave height of 1.02m for the period, also a substantial increase from average wave heights of .69m during the summer season.

Of all 9 storms which grounded during the early fall, Hurricane Sandy was the most detrimental and by far the strongest storm to impact the coastline during this period. Six of the nine storms were categorized as weak, and had little to no impact on the coast line. Of the remaining 3 storms one was classified as moderate, one as significant, which befell the barrier complex only two weeks before Hurricane Sandy, classified as extreme. Not only did Hurricane Sandy sustain fast winds and large wave heights throughout the 101 hour period, but it fell upon an astronomical spring high tide, increasing damage done to the coastline comparatively if it had fallen upon a normal or neap tidal cycle.

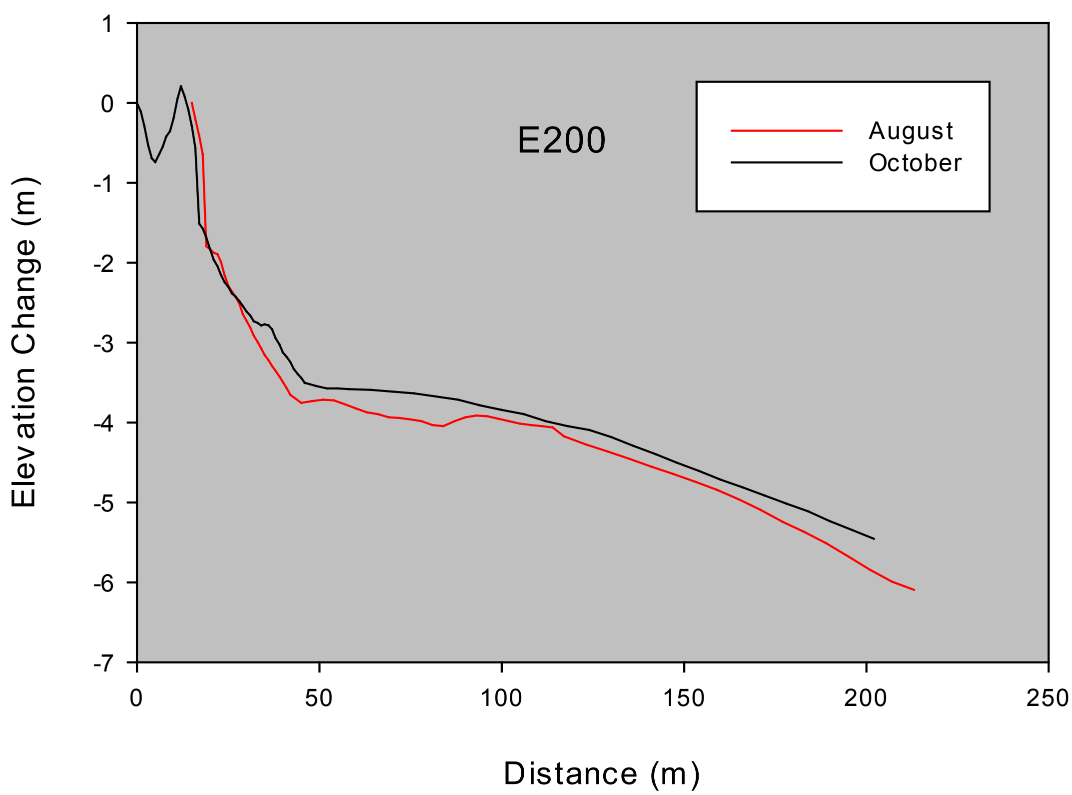


Figure 3.4a: Topographic profile results for E200 during the early fall period of 2012

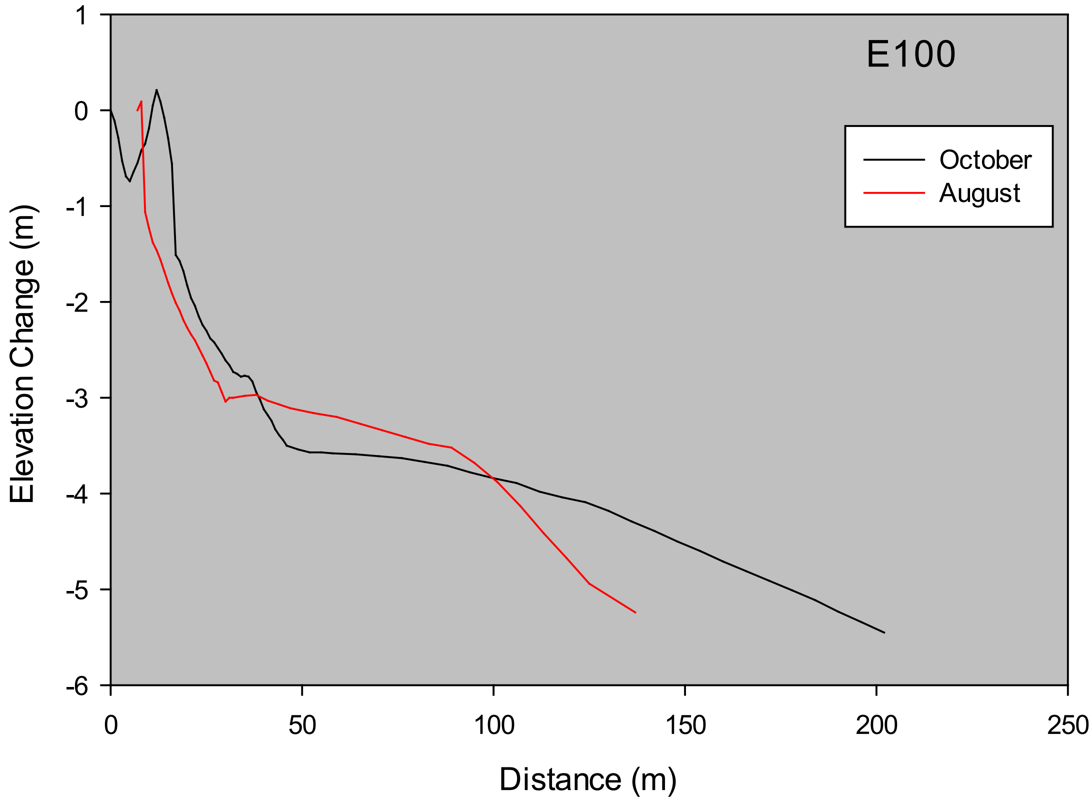


Figure 3.4b: Topographic profile results for E100 during the early fall period of 2012

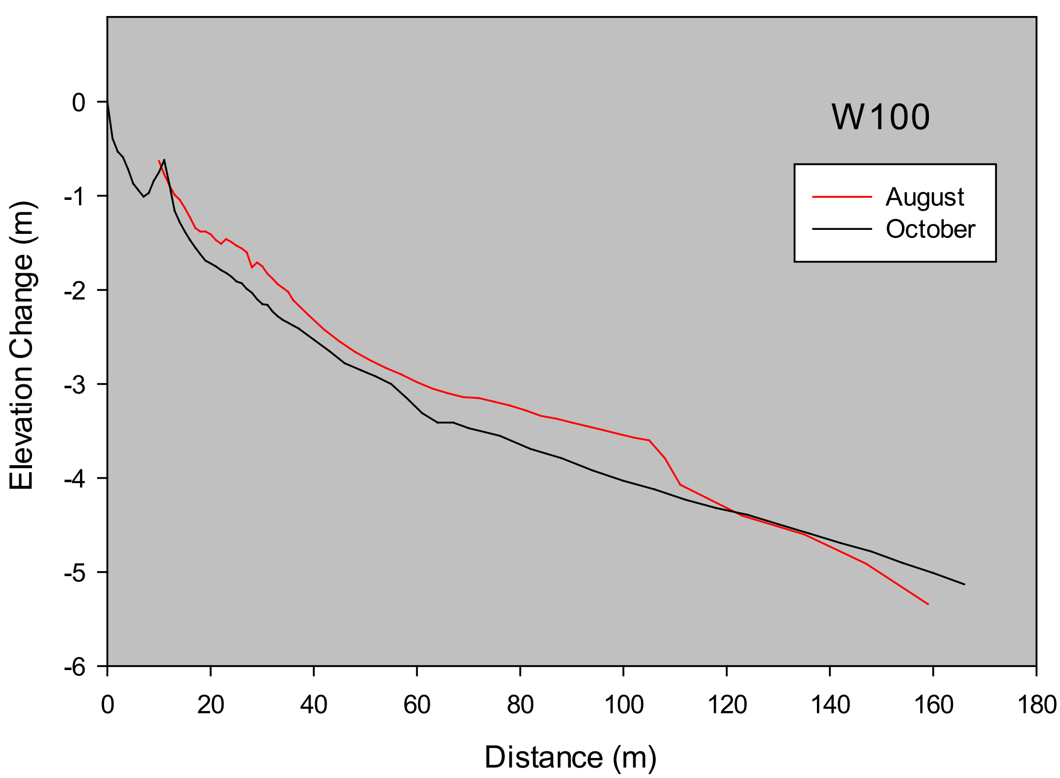


Figure 3.4c: Topographic profile results for W100 during the early fall period of 2012

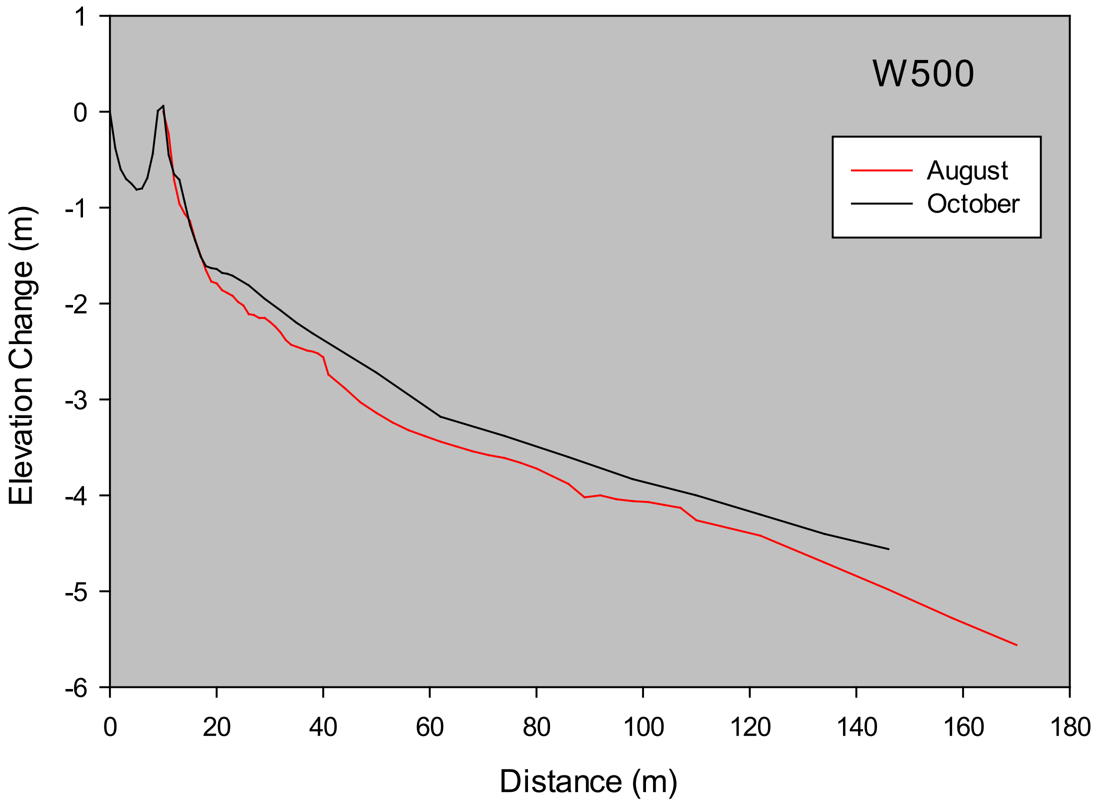


Figure 3.4d: Topographic profile results for W500 during the early fall period of 2012

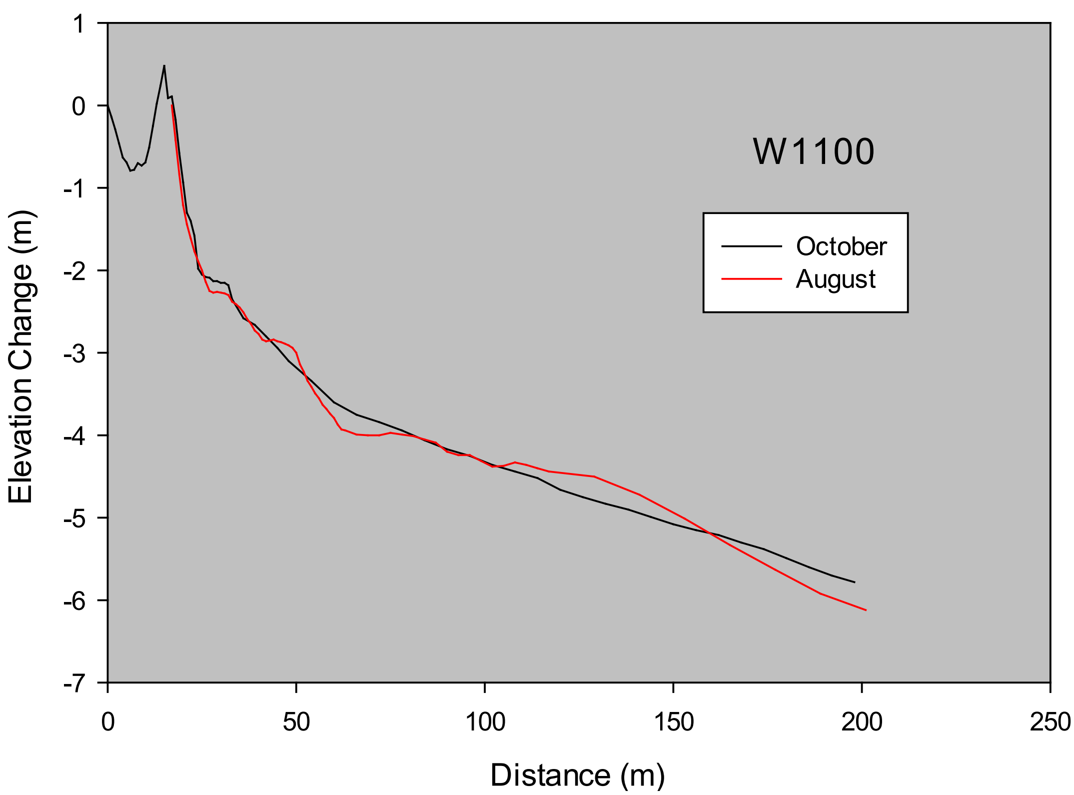


Figure 3.4e: Topographic profile results for W1100 during the early fall period of 2012

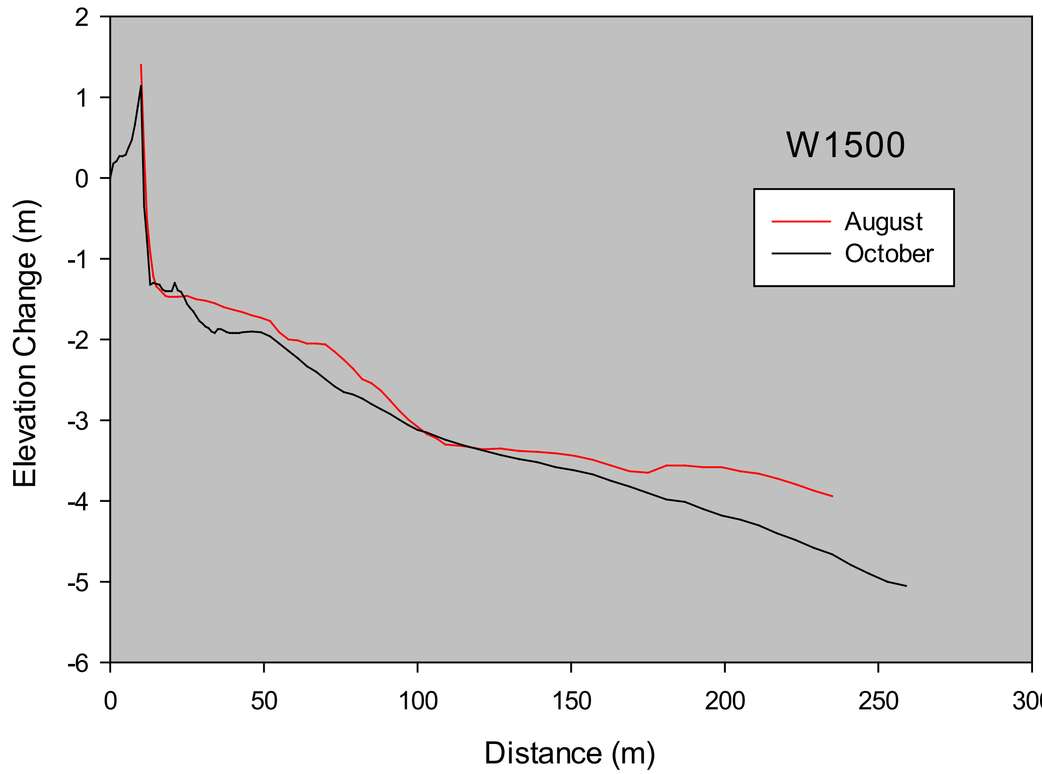


Figure 3.4f: Topographic profile results for W1500 during the early fall period of 2012

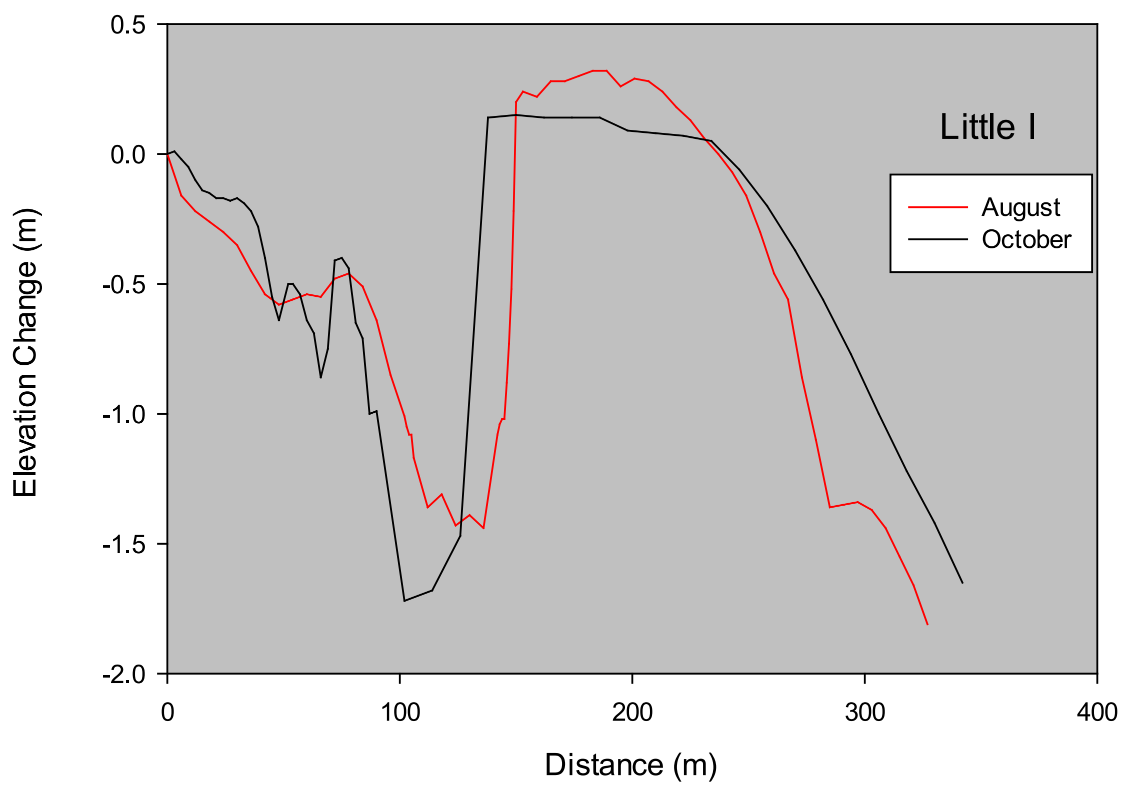


Figure 3.4g:Topographic profile results for Little Beach I during the early fall period of 2012

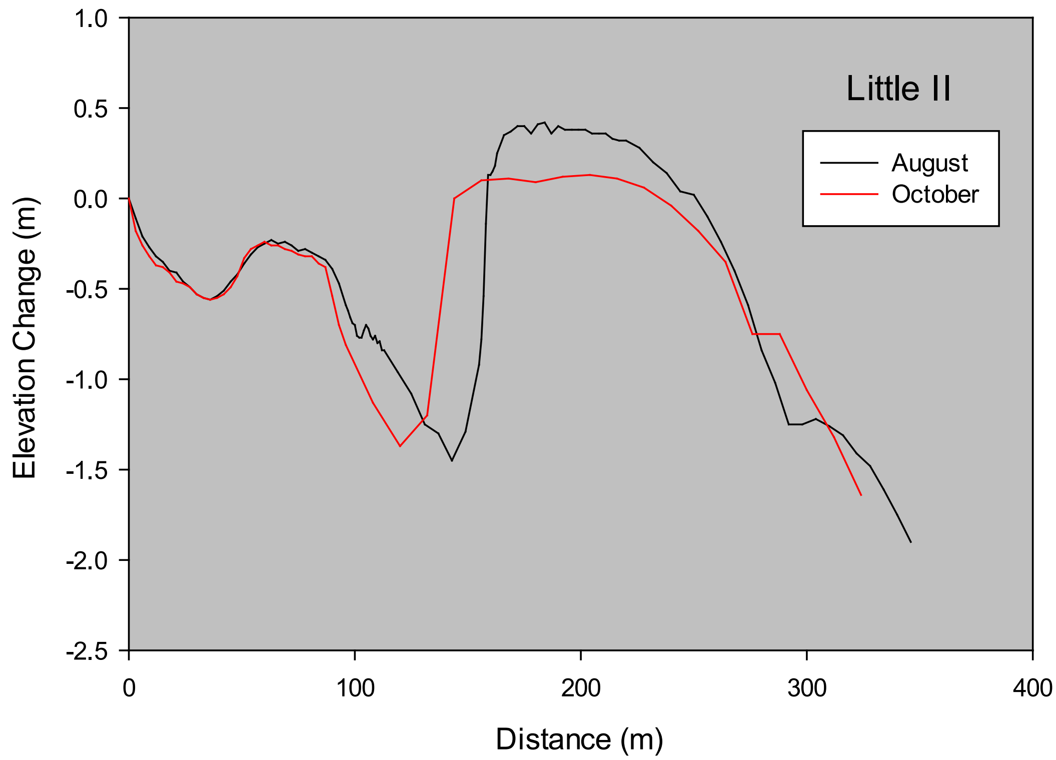


Figure 3.4h: Topographic profile results for Little Beach II during the early fall period of 2012

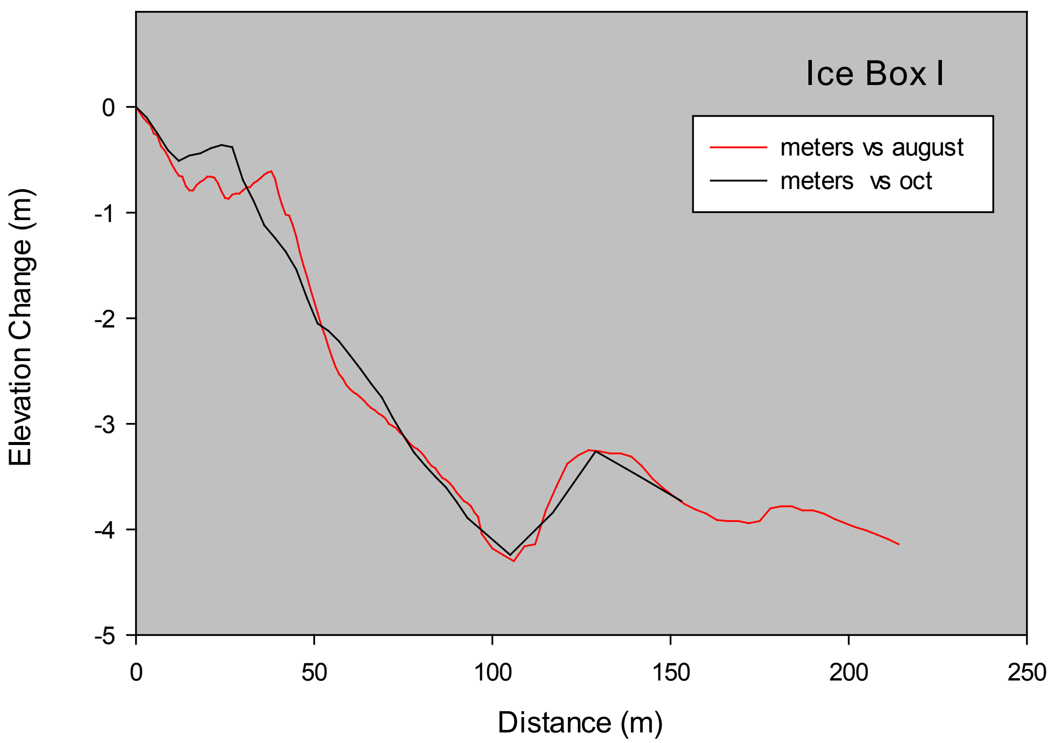


Figure 3.4i: Topographic profile results for Ice Box Beach I during the early fall period of 2012

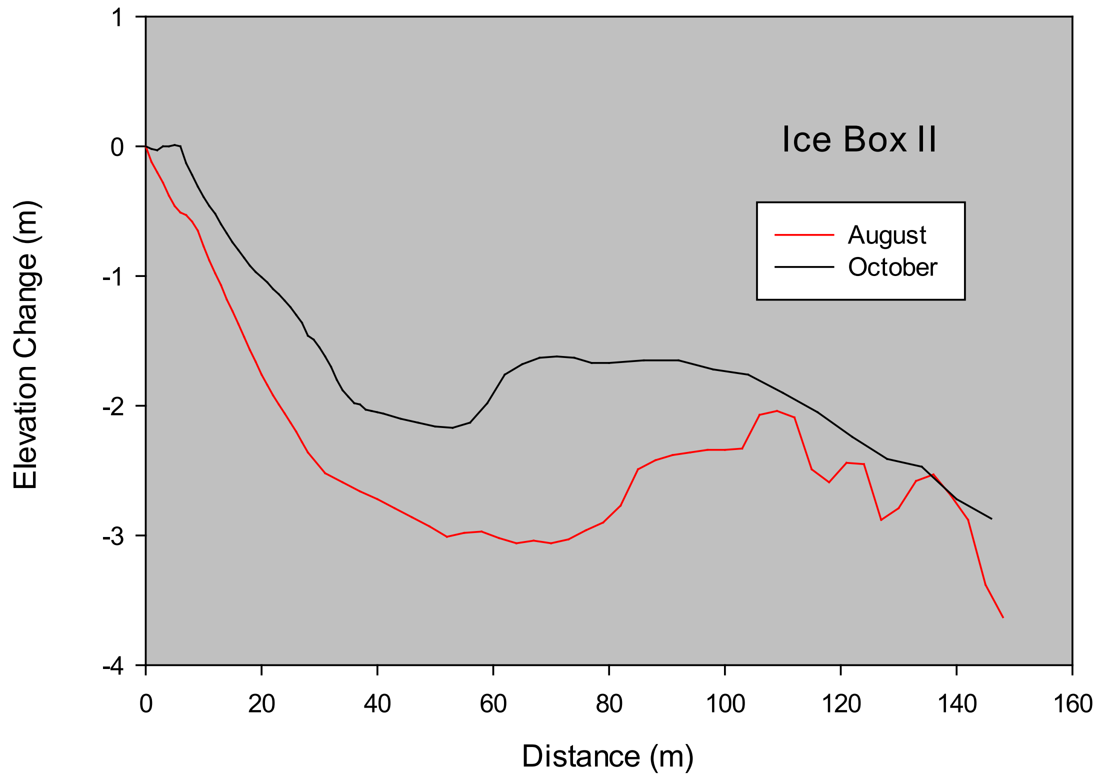


Figure 3.4j: Topographic profile results for Ice Box Beach II during the early fall period of 2012

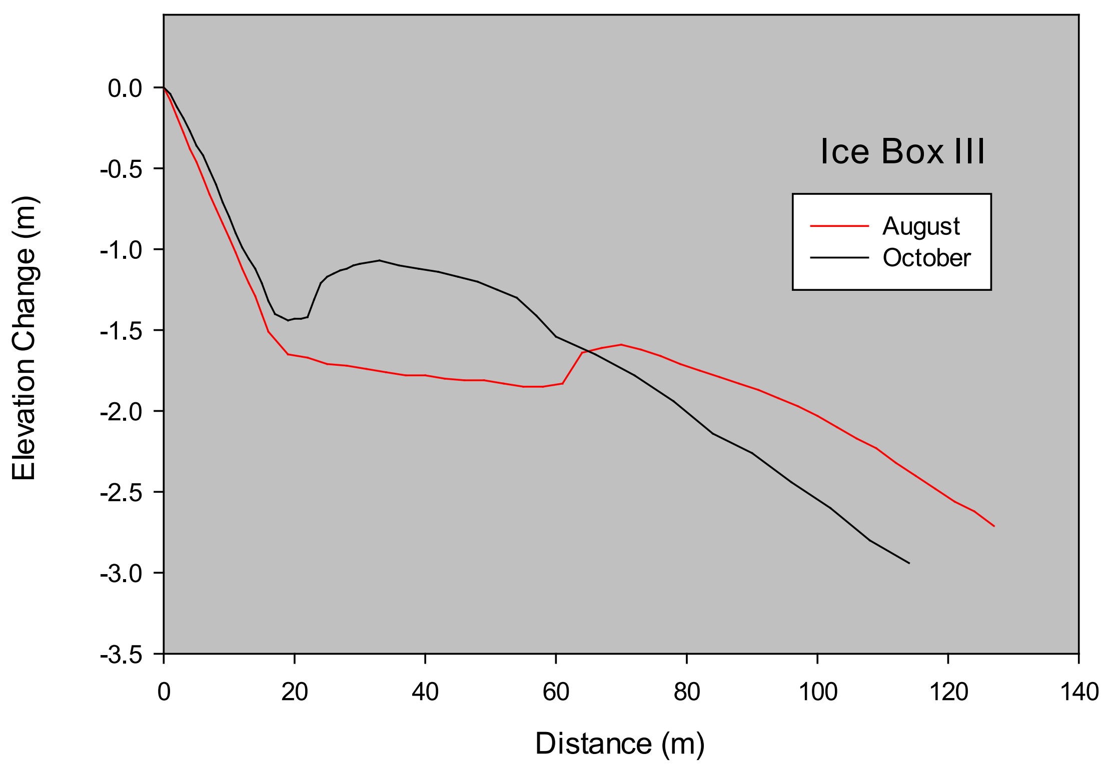


Figure 3.4k:Topographic profile results for Ice Box Beach III during the early fall period of 2012

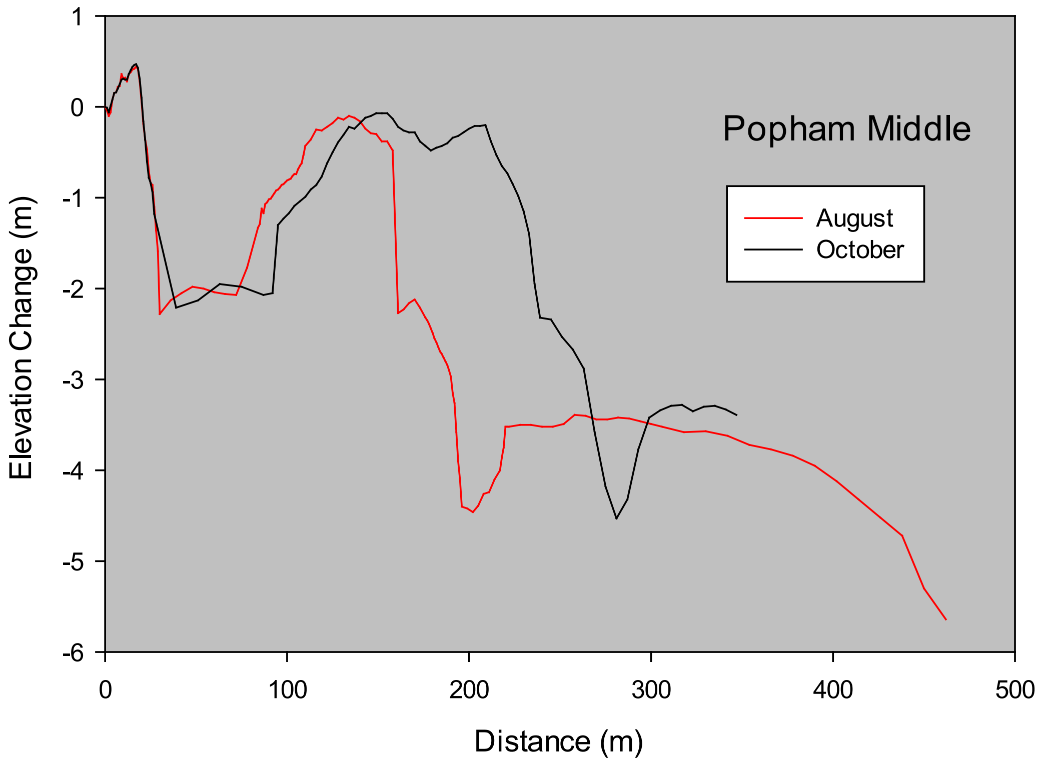


Figure 3.4l: Topographic profile results for West Bath House during the early fall period of 2012

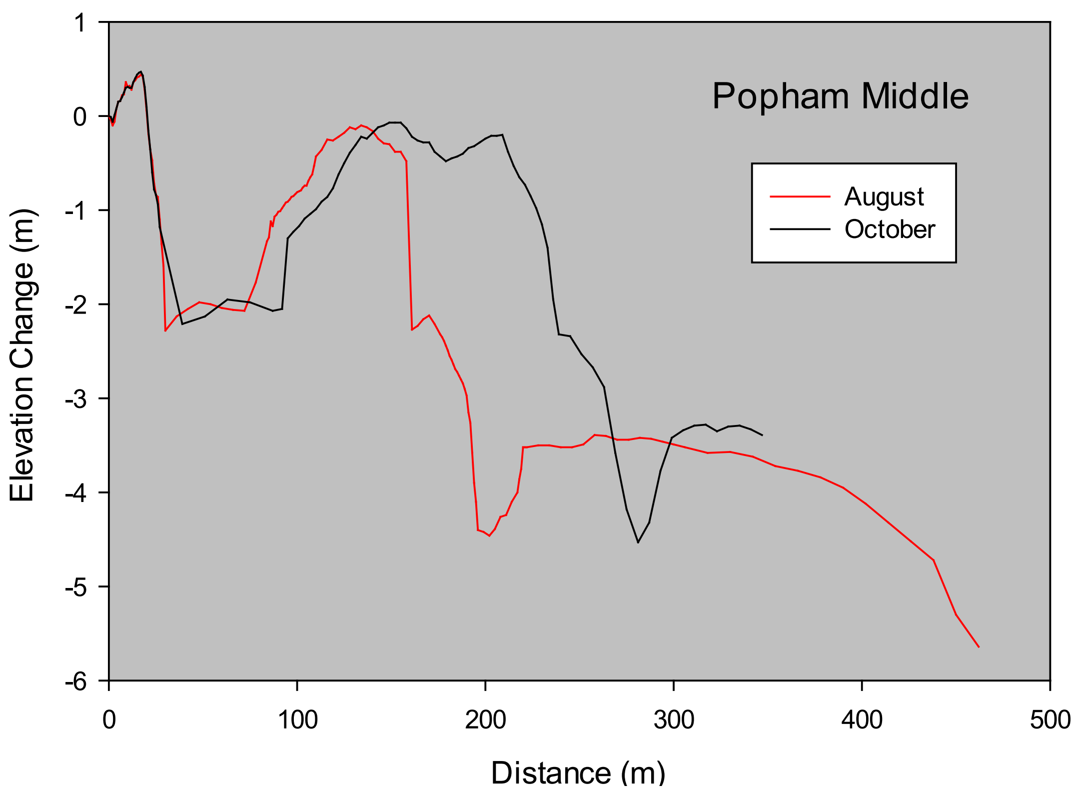


Figure 3.4m: Topographic profile results for Popham Middle during the early fall period of 2012

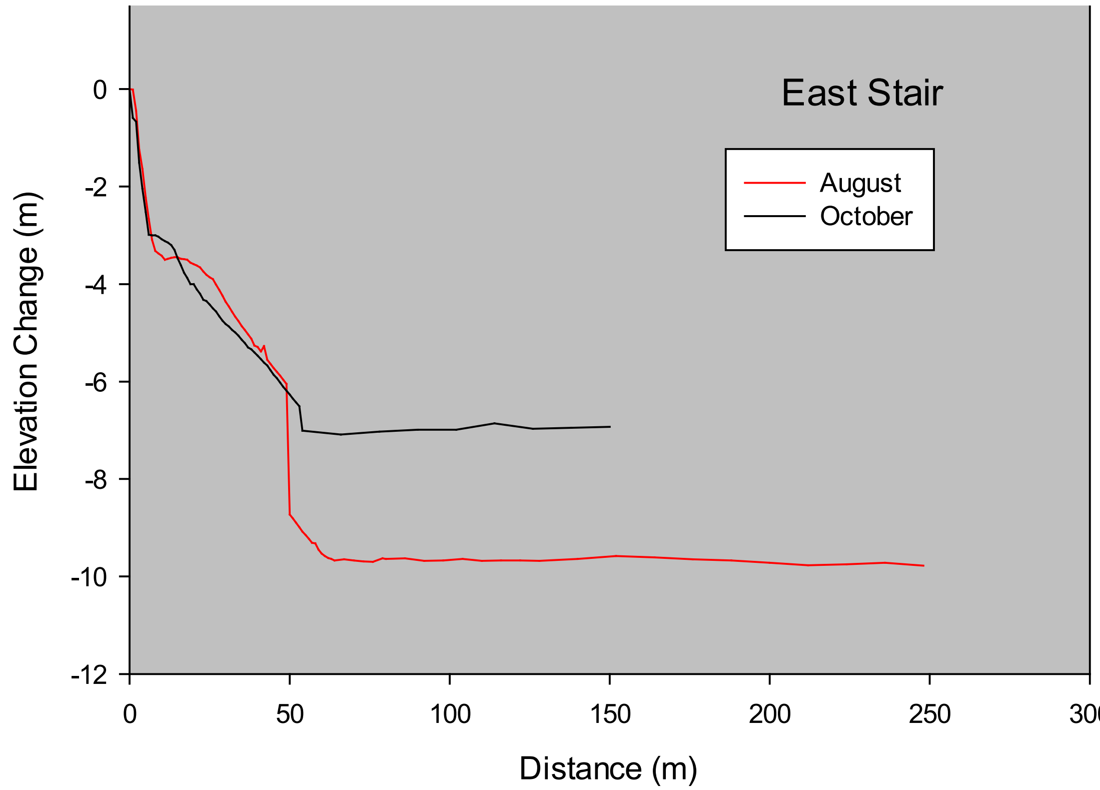


Figure 3.4n: Topographic profile results for East Stair during the early fall period of 2012

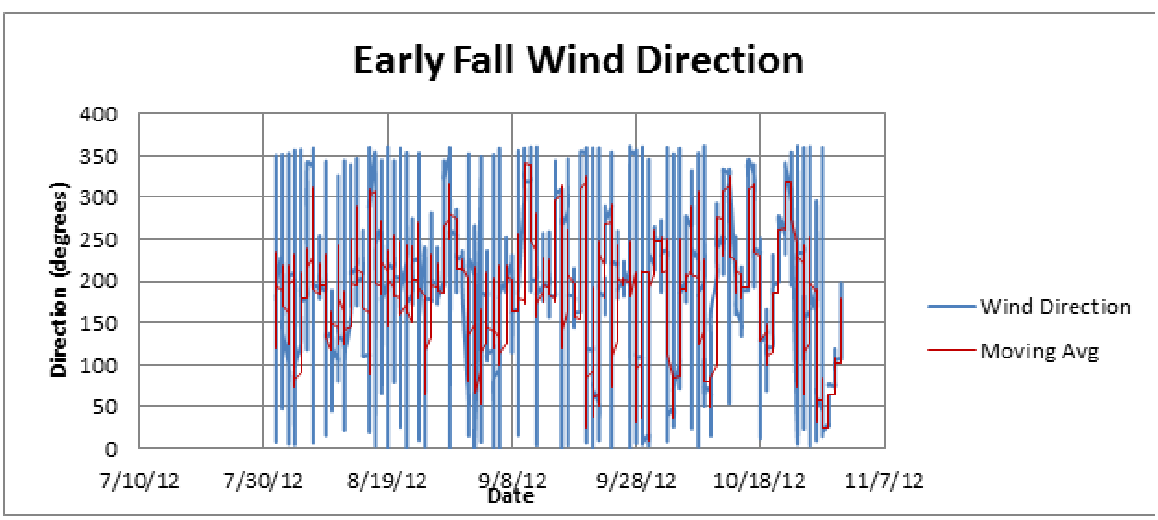


Figure 3.5a: Wind direction (degrees) from Buppy 44007 during the early fall period

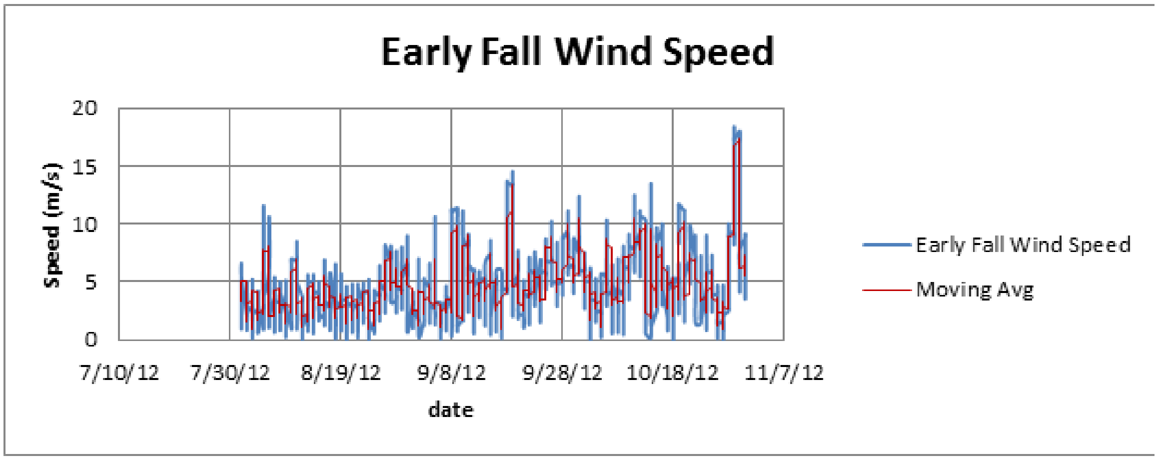


Figure 3.5b: Wind speed (m/s) from Buppy 44007 during the early fall period

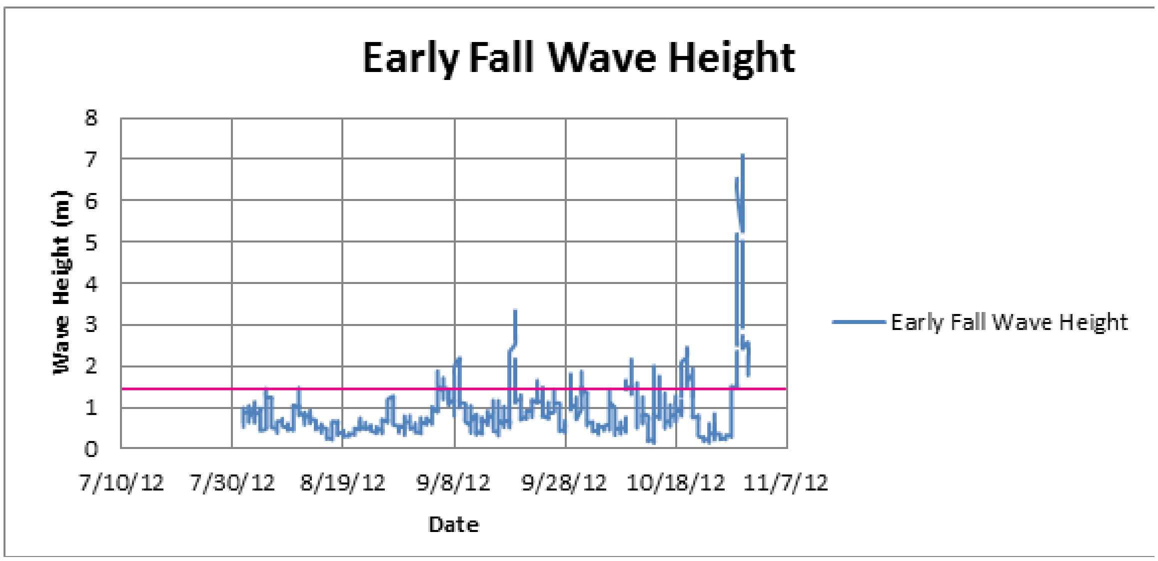


Figure 3.5c: Wave height (m) from Buppy 44007 during the early fall period

3.2.3 Late Fall Profiles and Weather Data

Late fall profile results for the barrier complex are shown in Figures 3.6a-n. All profiles include changes induced by activity of Hurricane Sandy and Winter Storm Athena, which lasted from October 28th to November 9th.

Profiles E100, W100, and W1100 all experienced accretion and thus growth of the berm as a result of the storm activity during this period. Profile E100 (Figure 3.6b) exhibits erosion past the plunge step, with an overall smoothed shore face, attributed to the slight accumulation of sand near the distal end of the berm. Profile W100 distinctly shows growth of the frontal dune ridge as well as the berm, with minimal change other than slight erosion of the low tide terrace (Figure 3.6c). Profile W1100 also shows minimal change from pre-storm profiles, with slight erosion at the top of the frontal dune ridge, slight accretion at the far extent of the berm, and only small erosion along the low tide terrace (Figure 3.6e).

Profiles W500 and W1500 (Figures 3.6d, f)) show evidence of extensive erosion along transects. Transect W500 has no change to the frontal dune ridge, however slight accretion at the beginning of the berm coupled with consistent erosion along the transect allows for a smoothed beach face, with a characteristic erosional profile. Profile W1500 experienced much more extensive amounts of erosion along the beach face. As the berm features were minimal initially, storm activity eroded the feature, creating a steepened, smoothed beach face with almost no transition from dune to shore face, stereotypical of an erosional or winter profile (Nelson and Fink, 1980). Sand from W1500 seems to have been moved by long shore transport and reworked onto the pocket beaches adjacent to the headland. Little Beach I and II (Figures 3.6g-h) show evidence that sand from W1500 was reworked onto the end of the southern Seawall spit, as the Sprague River Channel migrated west allowing continued growth of the spit and in fill of the eastern channel bank. Both profiles have erosion occurring along the length of the recreational beach, with enhancement of a ridge and runnel system. Ice Box I (Figure 3.6i) experienced intense erosion as a result of the two storms mentioned, and now exhibits a very steep and smooth beach face, with no berm features near the headland, as all constructional features have been eroded away. Profiles Ice Box II and III (Figures 3.6j-k) show possible evidence of this eroded sand being reworked onshore from Ice Box I. Although Ice Box II does have slight erosion to the berm feature near the base of the headland, the majority of the transect has experienced accretion, causing a flattening to the profile by filling in and eroding from the runnel and ridge system, respectively. Ice Box III mimics Ice Box II; however no change occurred adjacent to the headland over the course of the storms.

Weather data for the period is provided in Figures 3.7a-c. As expected, weather conditions continued to increase in intensity from early fall into late fall. Wind speeds averaged at 6.07 m/s from the south, and wave heights averaged at 1.06m, slightly higher than in the early fall. Maximum wind speeds of 18.4 m/s and a maximum wave height of 7.11m for this period resulted from Hurricane Sandy, as did the early fall period.

There were 11 total storms during October and November, 6 being weak, 1 moderate, 2 significant, 1 severe, and 1 extreme (Table 1). Hurricane Sandy was the only extreme storm of the period, and as in the early fall, was the most detrimental storm to hit the coast during this period due to a combination of factors including duration, sustained high wind speeds and high wave heights, and the coincidence with spring tides as described in section 3.22 above.

The next strongest storm with a power of 1496.92 was Winter Storm Athena, which lasted 42 hours from November 7th to the 9th (Table 3.1). During the storm Maximum wind speeds were 16.5 m/s, and sustained wind speeds averaged 13.9 m/s from the northeast. Wave heights maxed out at 5.97m, with average wave heights of 3.13m in her 42 hour duration. Although Winter Storm Athena had higher sustained wind speeds and wave height than Hurricane Sandy, the storm lasted less than half the duration of the hurricane at 101 hours. Furthermore, the winter storm did not coincide with an astronomically high spring tide as did Hurricane Sandy. Winter storm Athena fell on a third quarter moon and thus an astronomically low or neap tidal cycle, therefore erosion despite intense wind speeds and wave heights was at its lowest effectiveness, and it was not as influential as Hurricane Sandy. However in combination, Hurricane Sandy and Winter Storm Athena had detrimental effects in terms of forcing on the Atlantic Coastline as less than a week of recovery time separated the two storms.

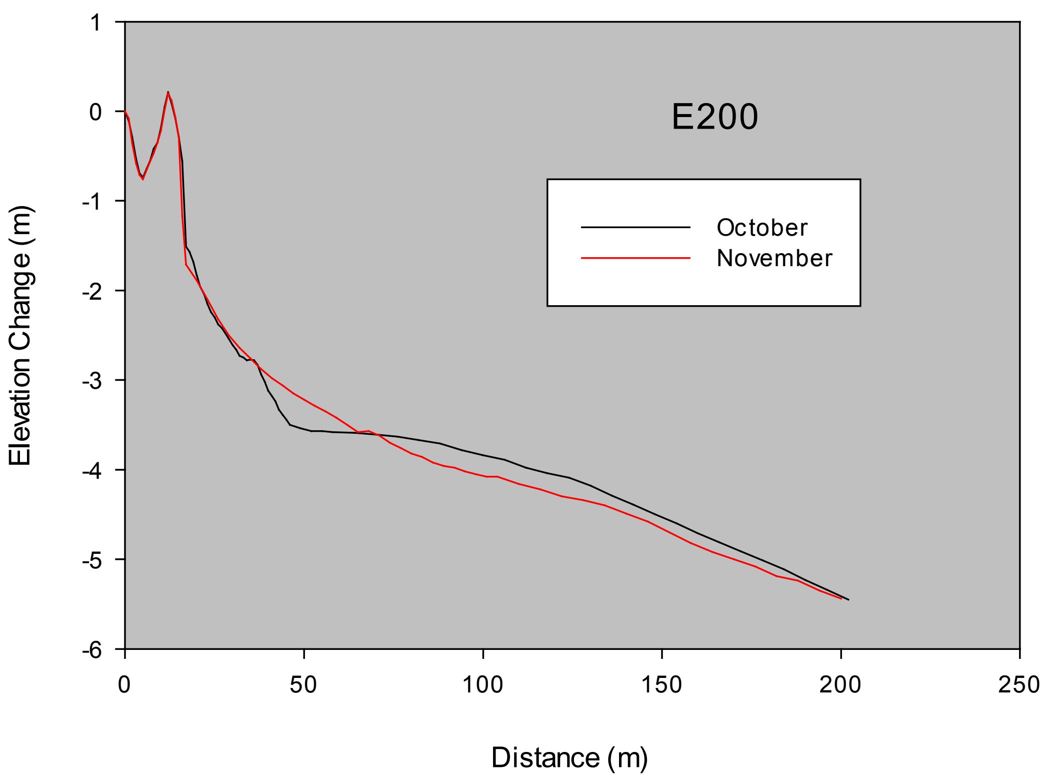


Figure 3.6a: Topographic profile results for E200 during the late fall period of 2012

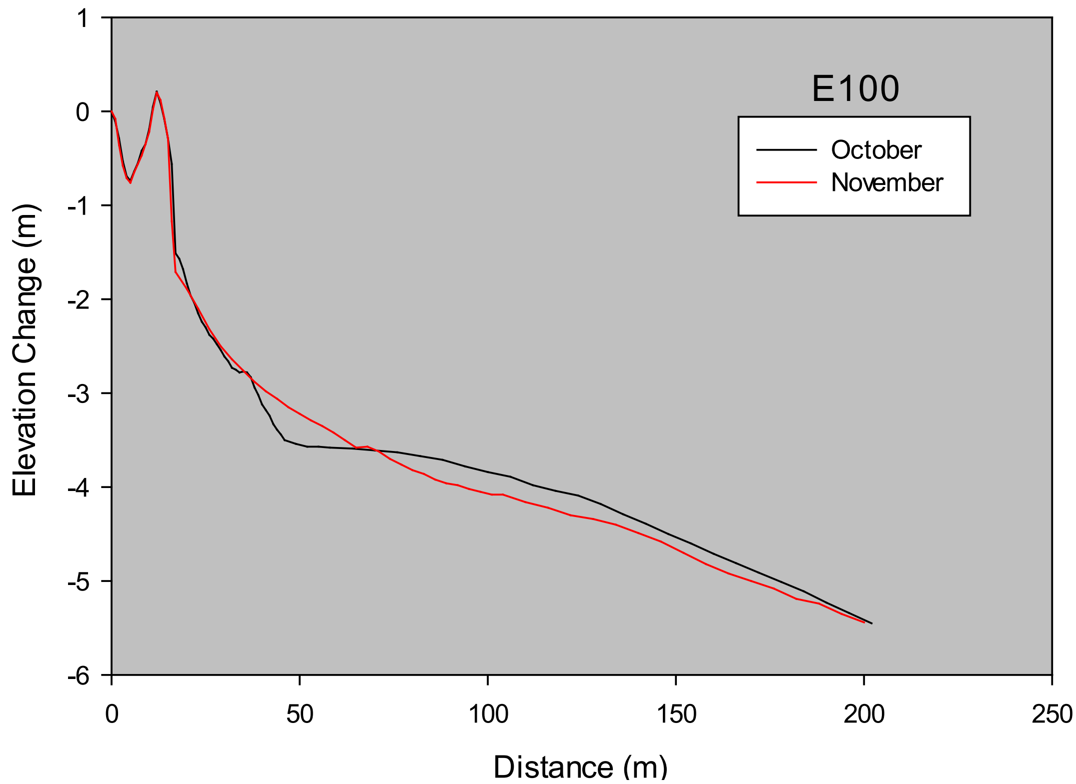


Figure 3.6b: Topographic Profile results from E100 during the late fall period of 2012

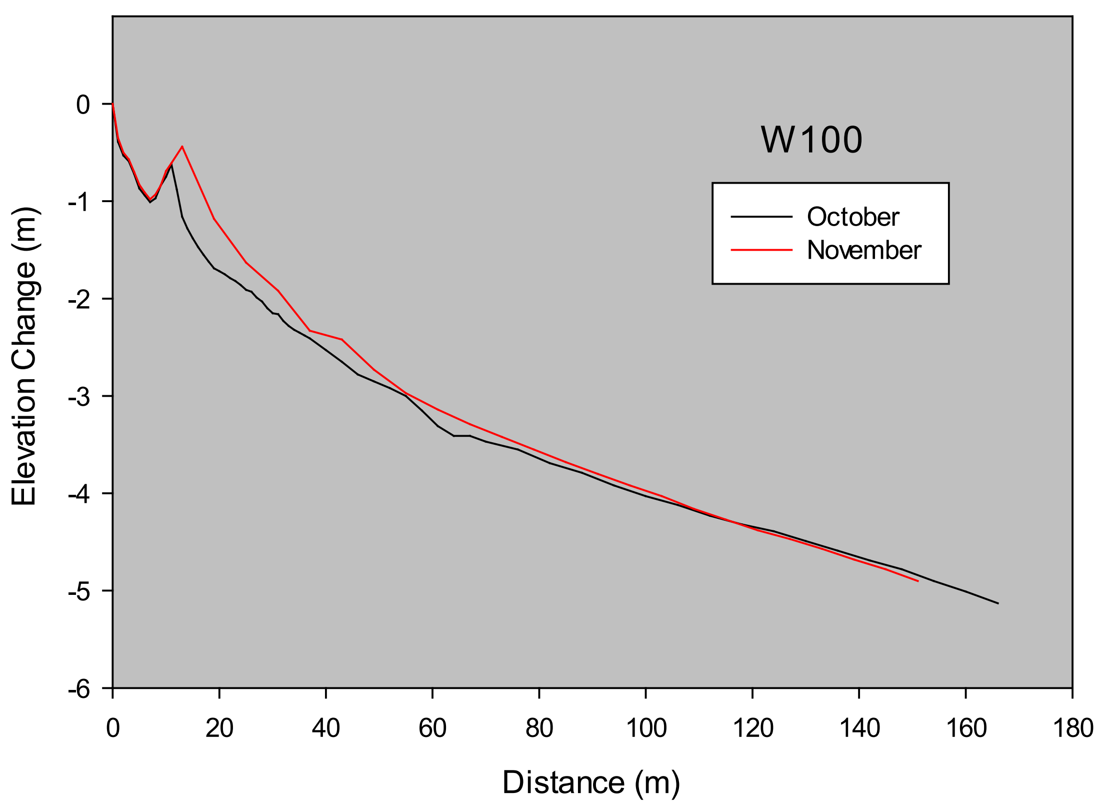


Figure 3.6c: Topographic Profile results from W100 during the late fall period of 2012

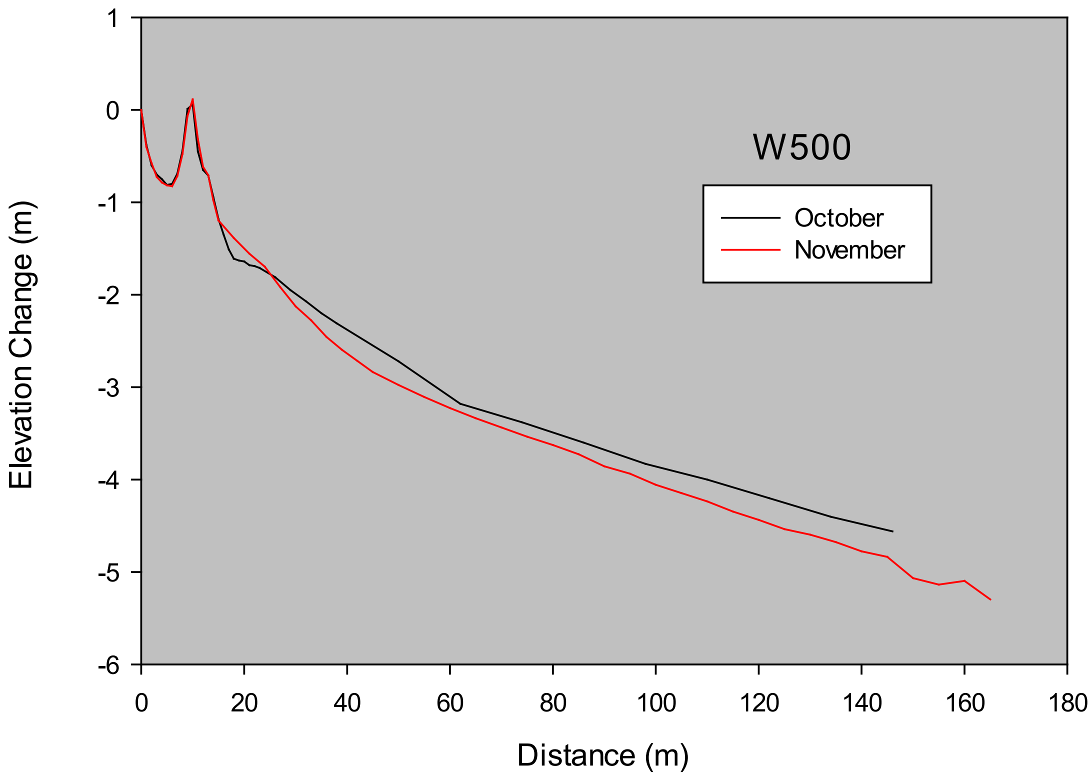


Figure 3.6d: Topographic Profile results from W500 during the late fall period of 2012

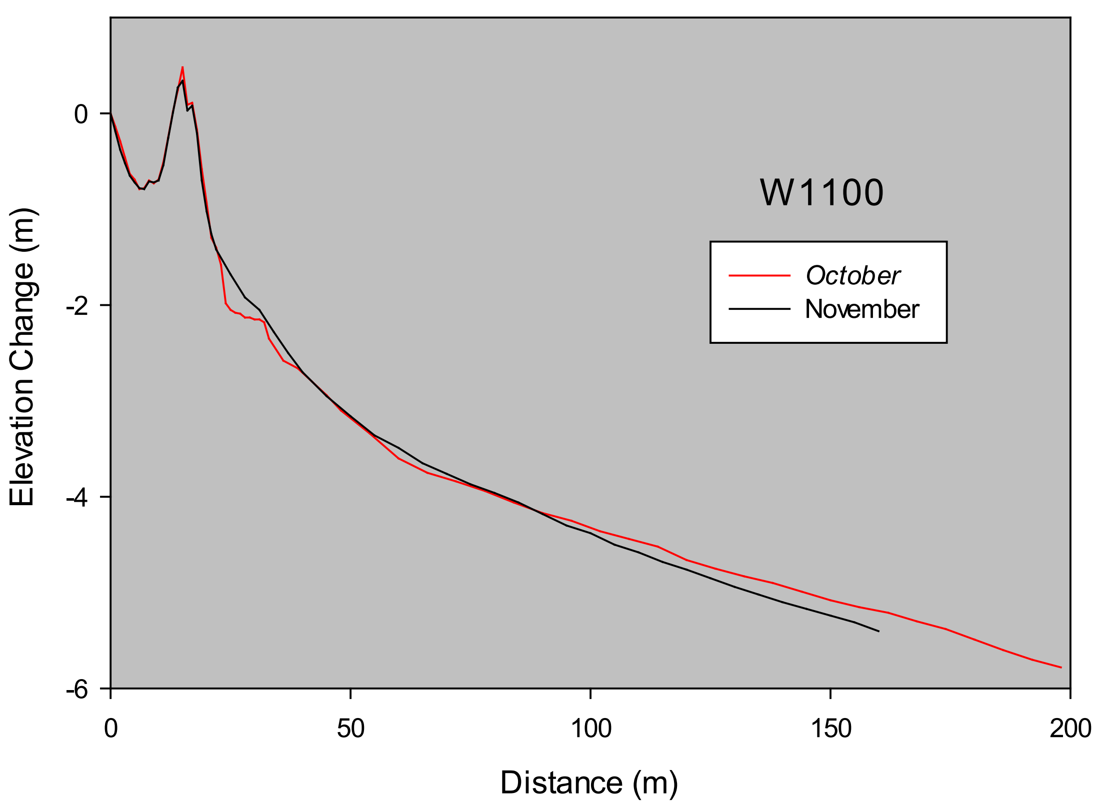


Figure 3.6e: Topographic Profile results from W1100 during the late fall period of 2012

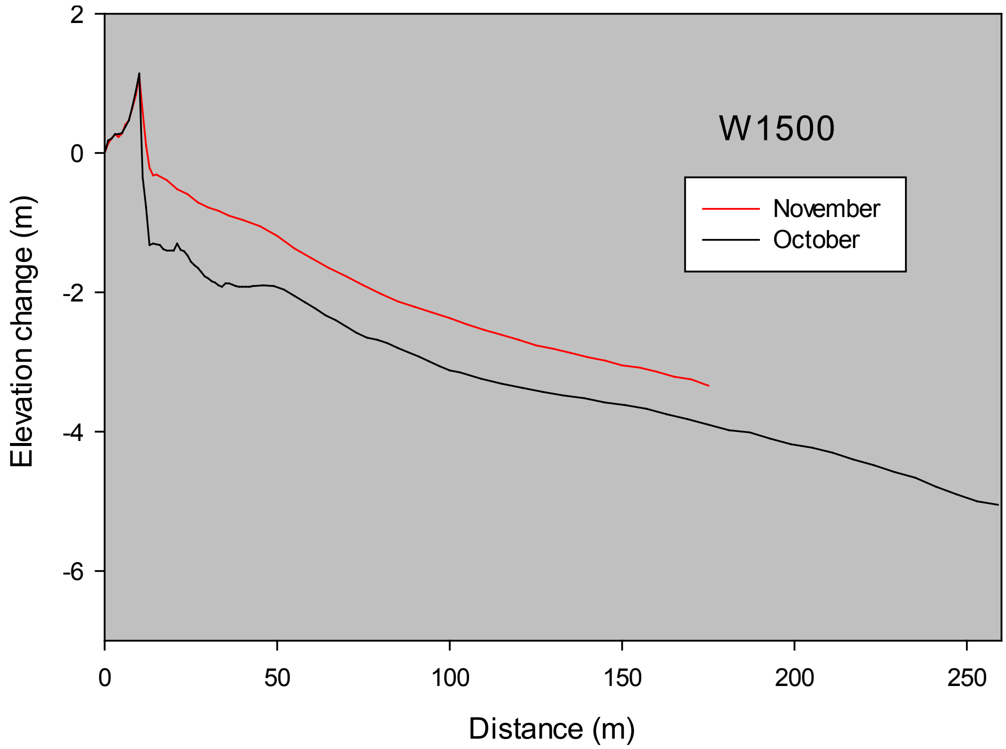


Figure 3.6f: Topographic Profile results from W1500 during the late fall period of 2012

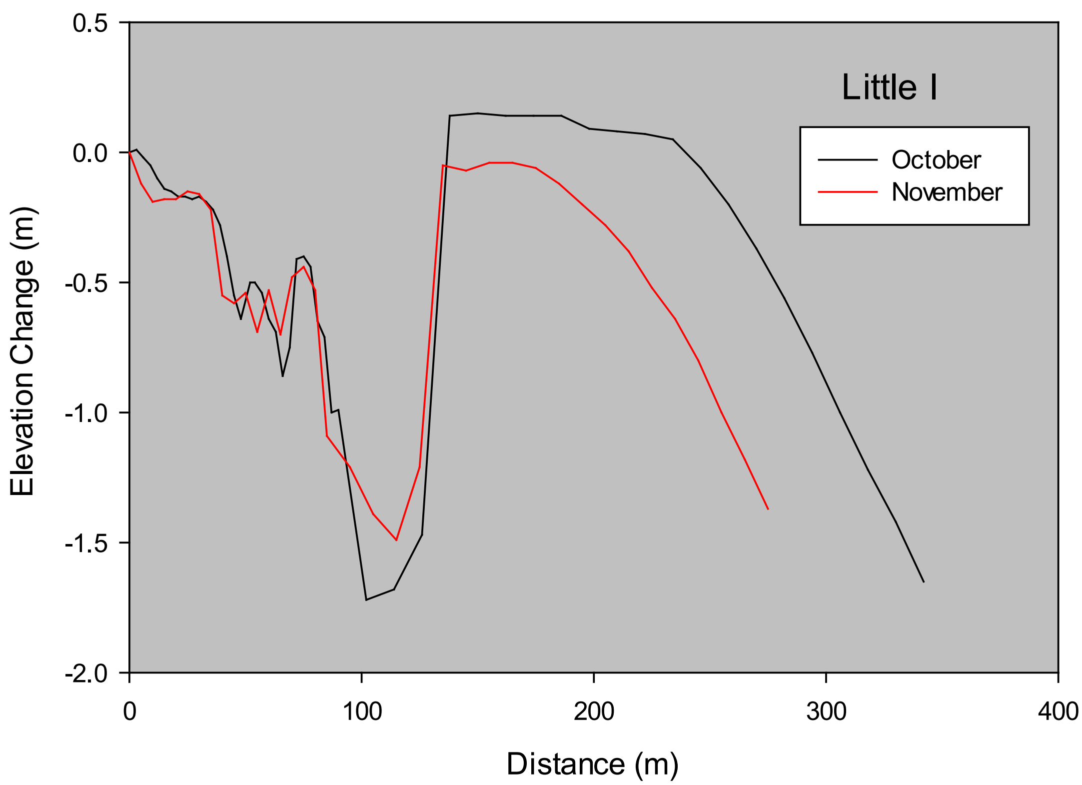


Figure 3.6g: Topographic Profile results from Little Beach I during the late fall period of 2012

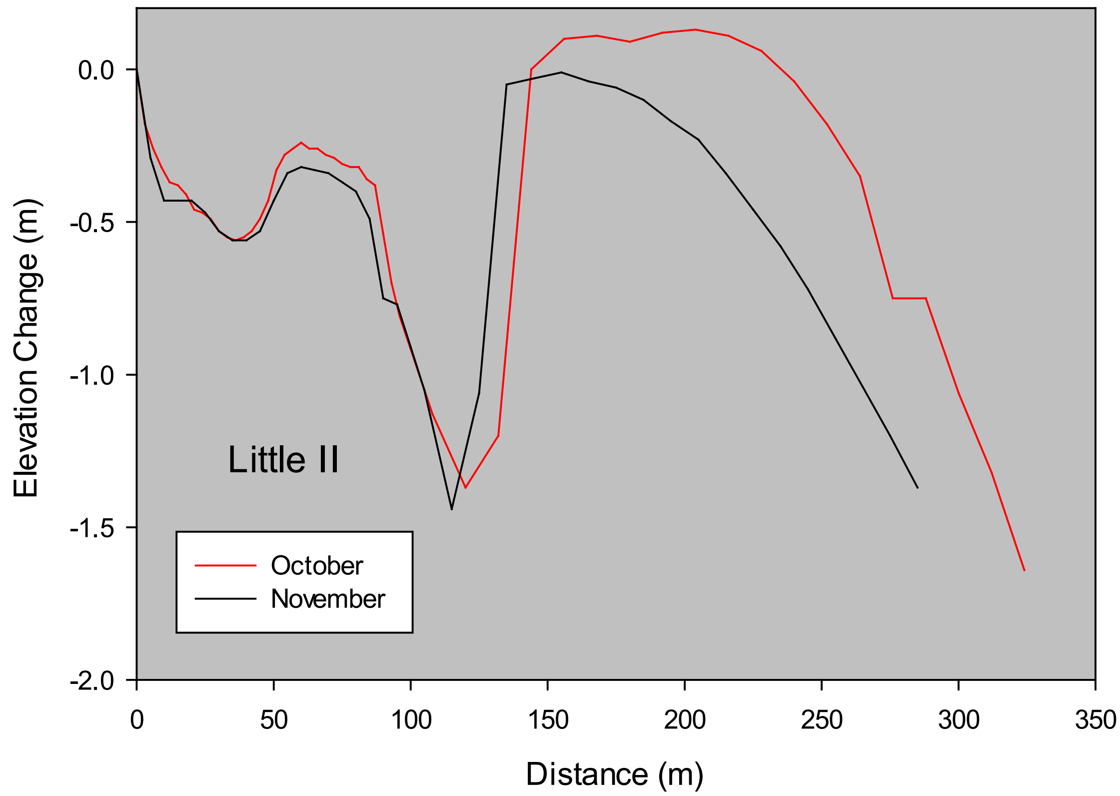


Figure 3.6h: Topographic Profile results from Little Beach II during the late fall period of 2012

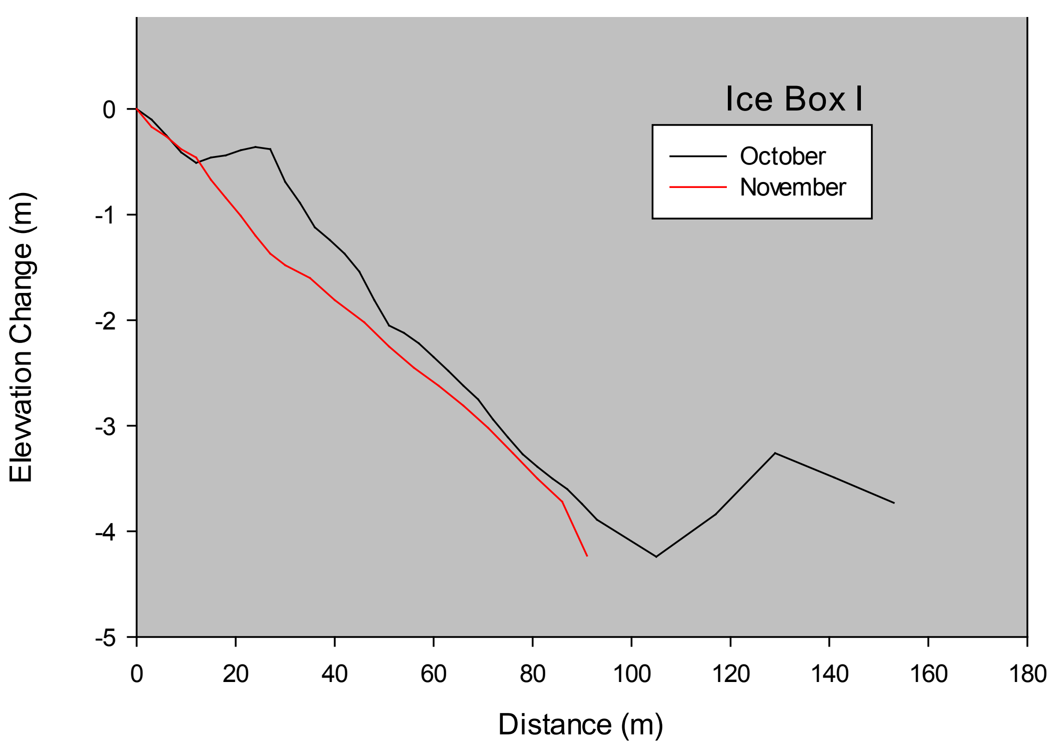


Figure 3.6i: Topographic Profile results from Ice Box Beach I during the late fall period of 2012

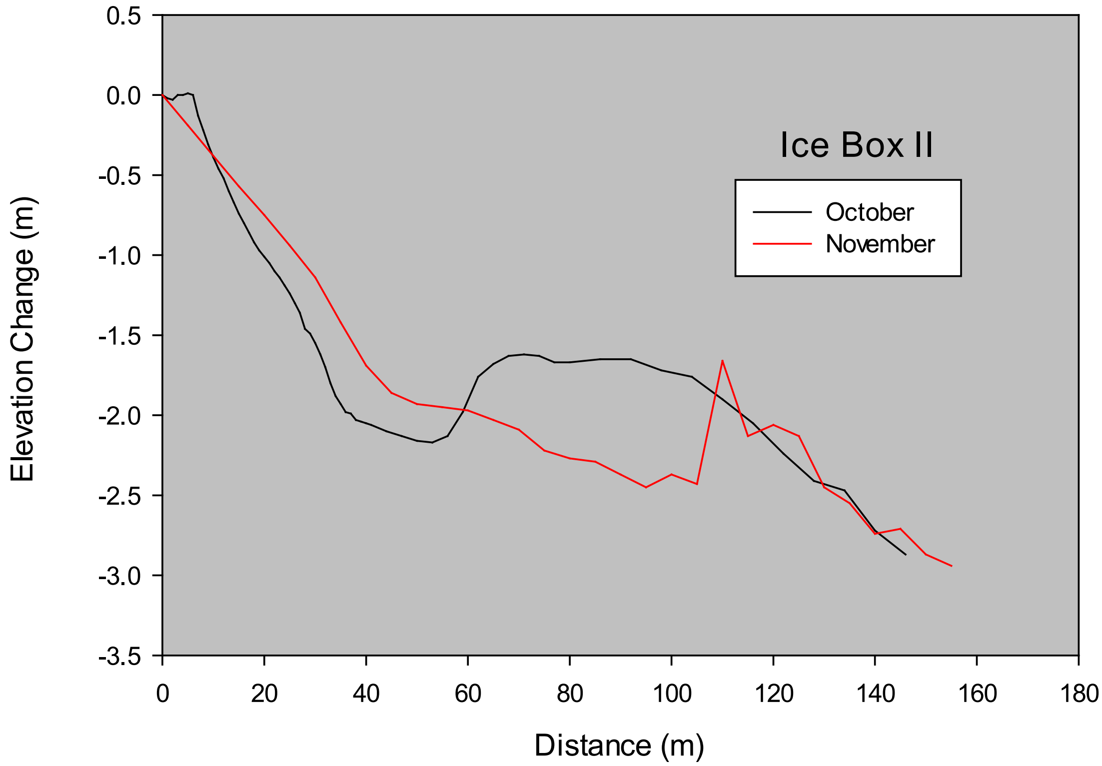


Figure 3.6j: Topographic Profile results from Ice Box Beach II during the late fall period of 2012

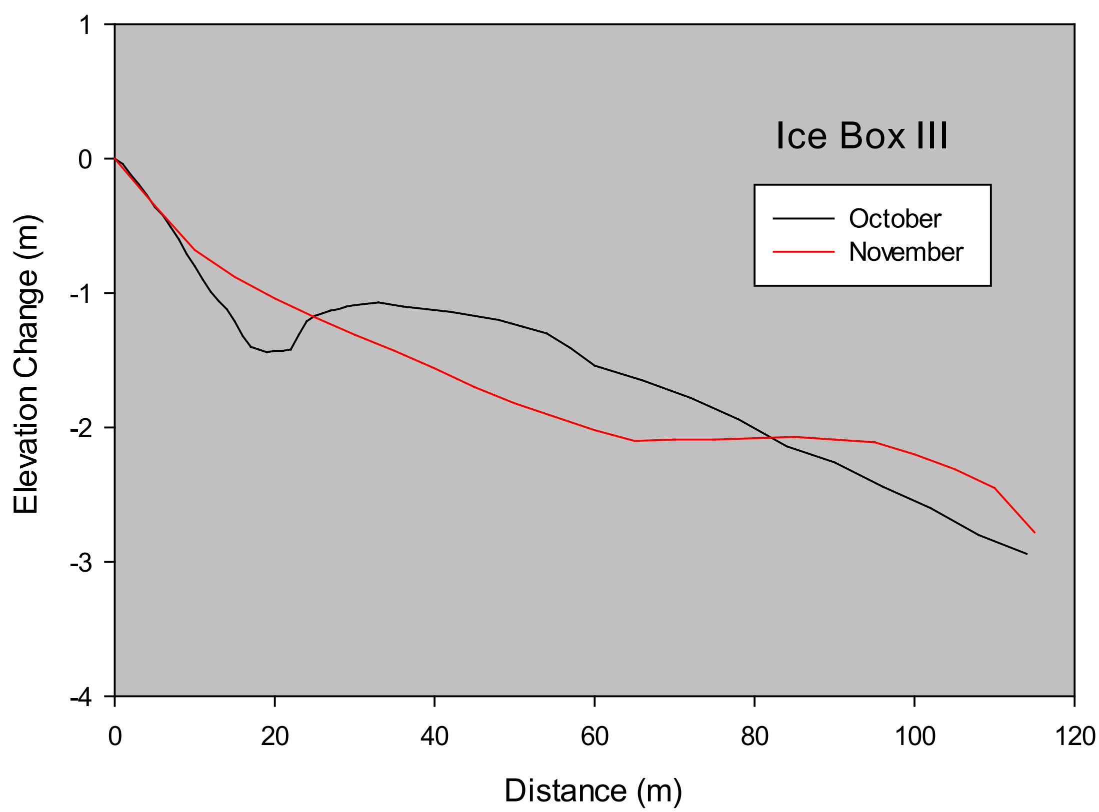


Figure 3.6k: Topographic Profile results from Ice Box Beach III during the late fall period of 2012

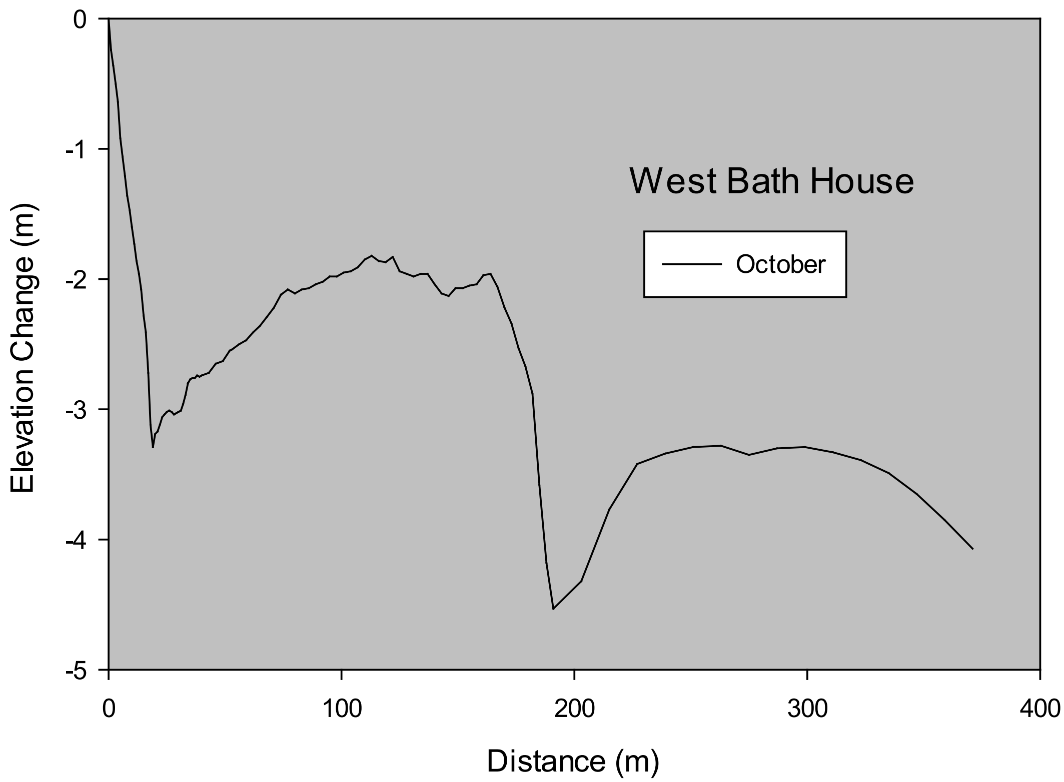


Figure 3.6l: Topographic Profile results from West Bath House during the late fall period of 2012

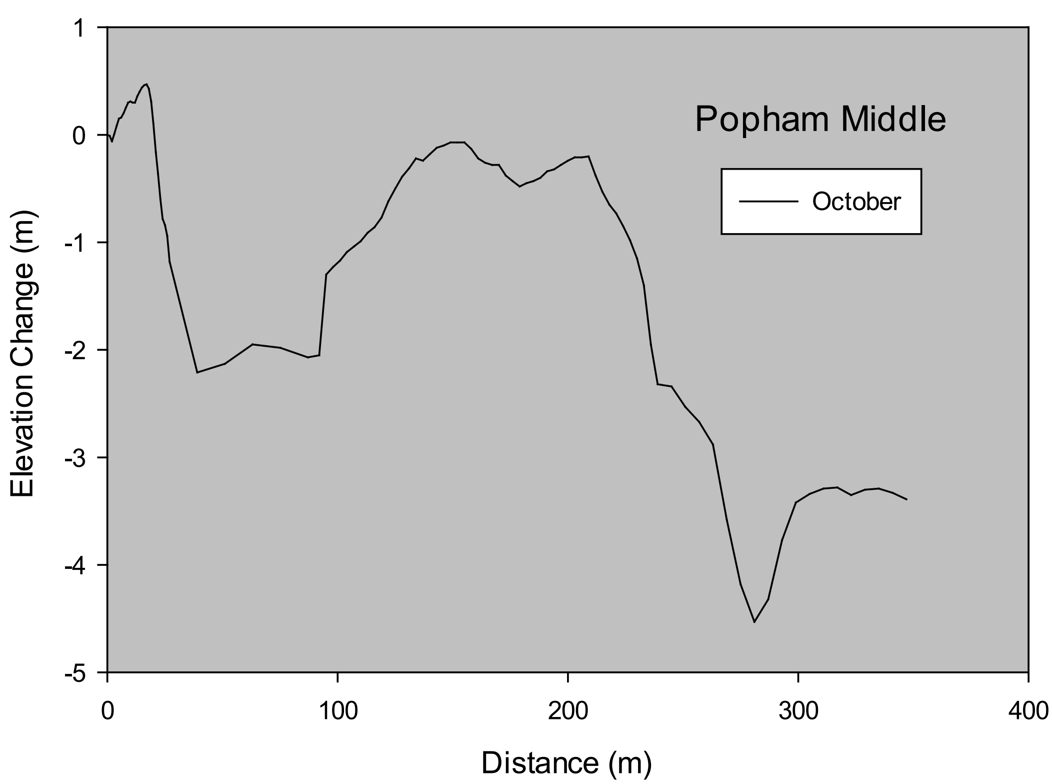


Figure 3.6m: Topographic Profile results from Popham Middle during the late fall period of 2012

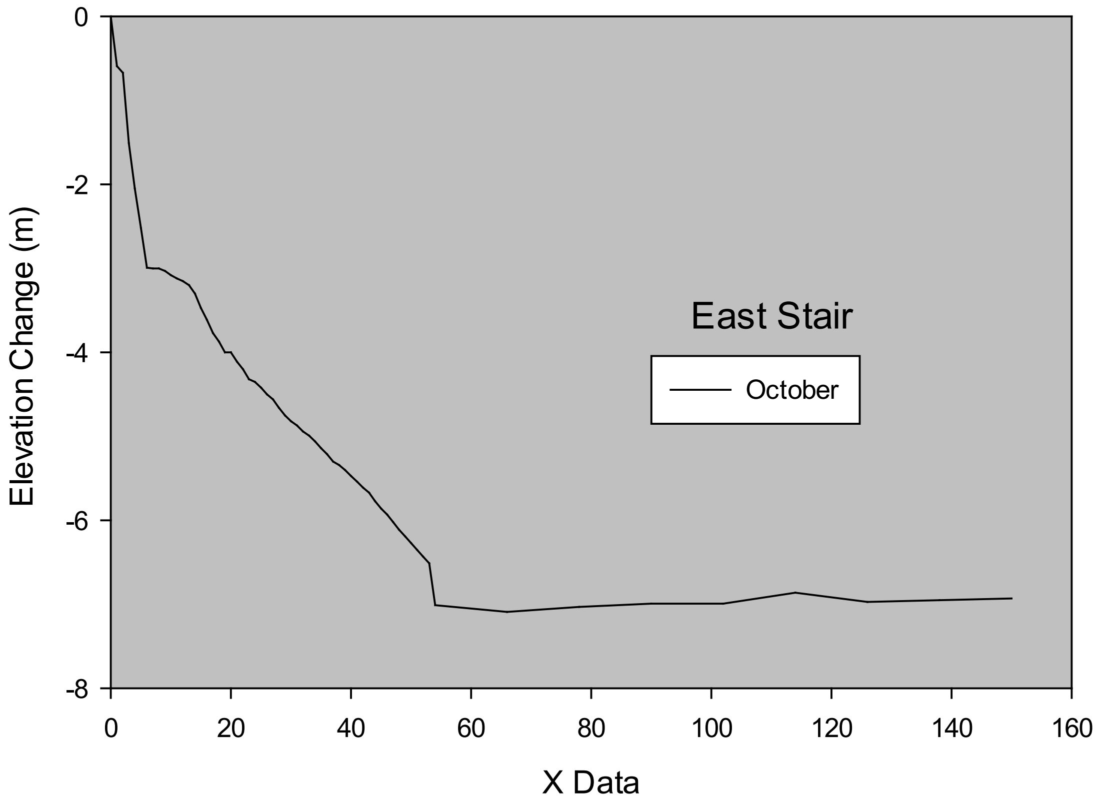


Figure 3.6n: Topographic Profile results from East Stair during the late fall period of 2012

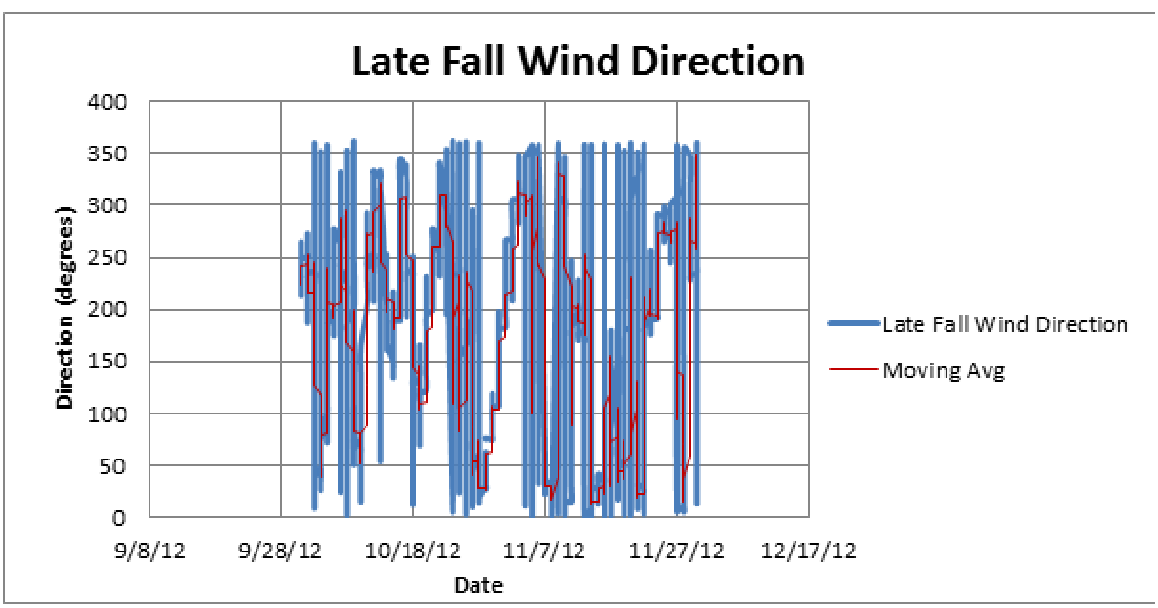


Figure 3.7a: Wind direction (degrees) from Buoy 44007 during the late fall study period of 2012

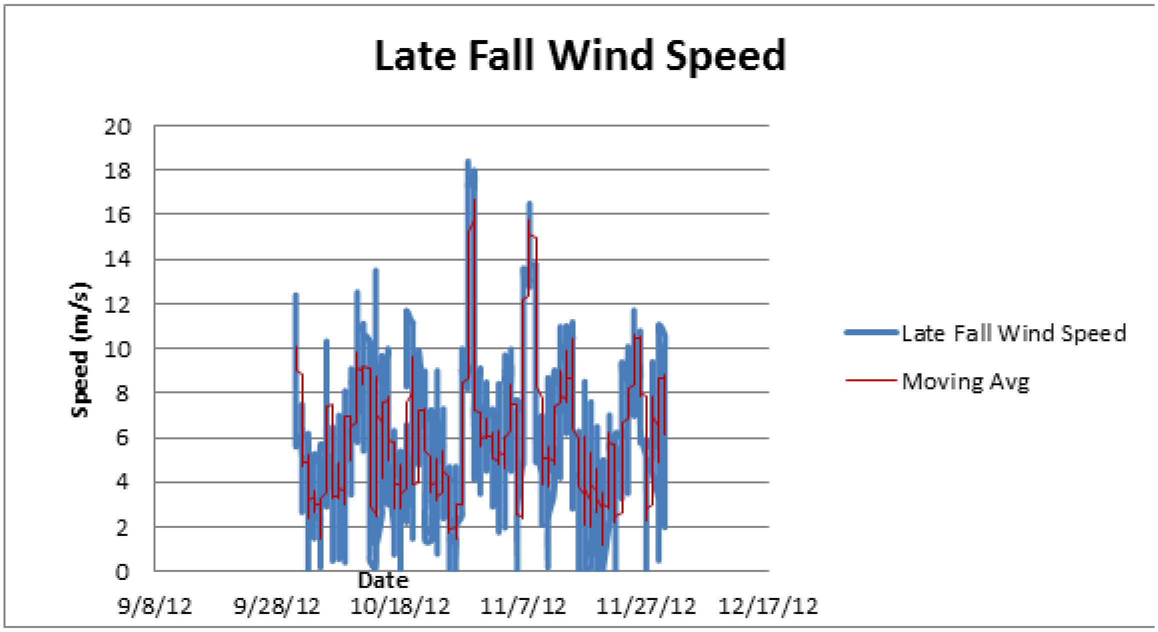


Figure 3.7b: Wind speed (m/s) from Buoy 44007 during the late fall study period of 2012

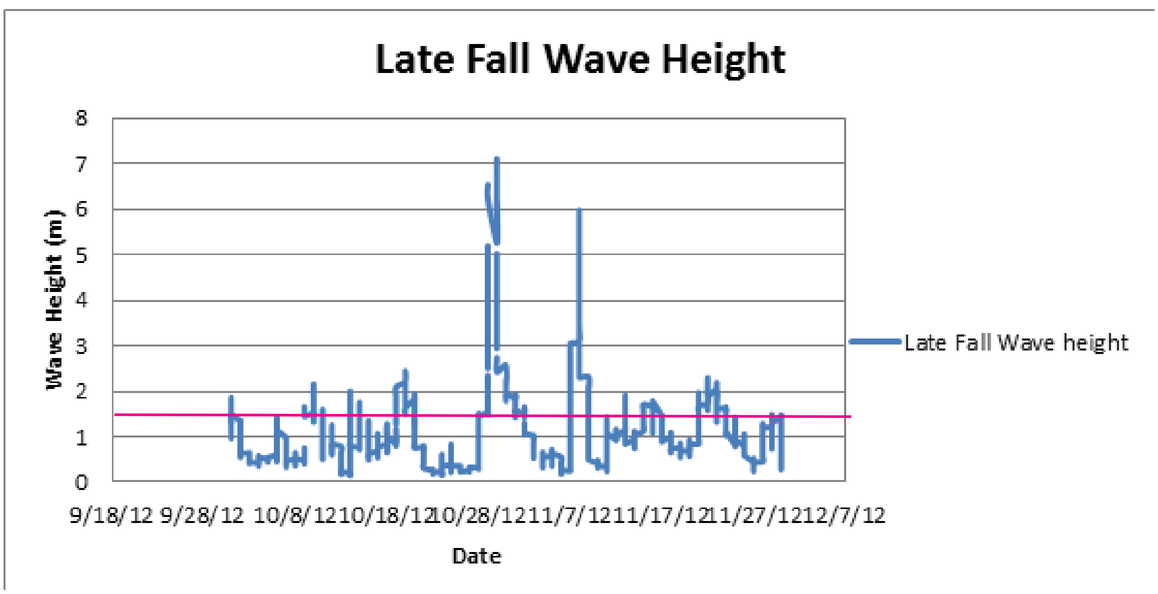


Figure 3.7c: Wave height (m) from Buoy 44007 during the late fall study period of 2012

3.3 Seasonal Inlet Morphology: GPS Tracks and Photography

3.3.1 Sprague River

GPS Tracks marking the low tide channel banks were recorded once during the summer season, in late August of 2012, and once during the fall season in late November of 2012. Tracks from 2009 were superimposed on the 2011 ortho image to be used as a baseline (Figure 3.8). A visible migration of the channel occurred towards the southern spit in the back barrier region from summer to fall, shown by the purple and blue tracks. Tracks show a general west to east migration of the river channel in front of Little Beach, forcing the meander to cut into the southwestern spit from summer to fall. The channel was anchored against the Cape Small headland until reaching bedrock outcrops on the low tide terrace of Ice Box Beach and the distal portion of the southwestern spit during all three periods. Here the channel swings eastward entering into the Atlantic. At this point the path has not varied much from the 2009 channel, shown in yellow.

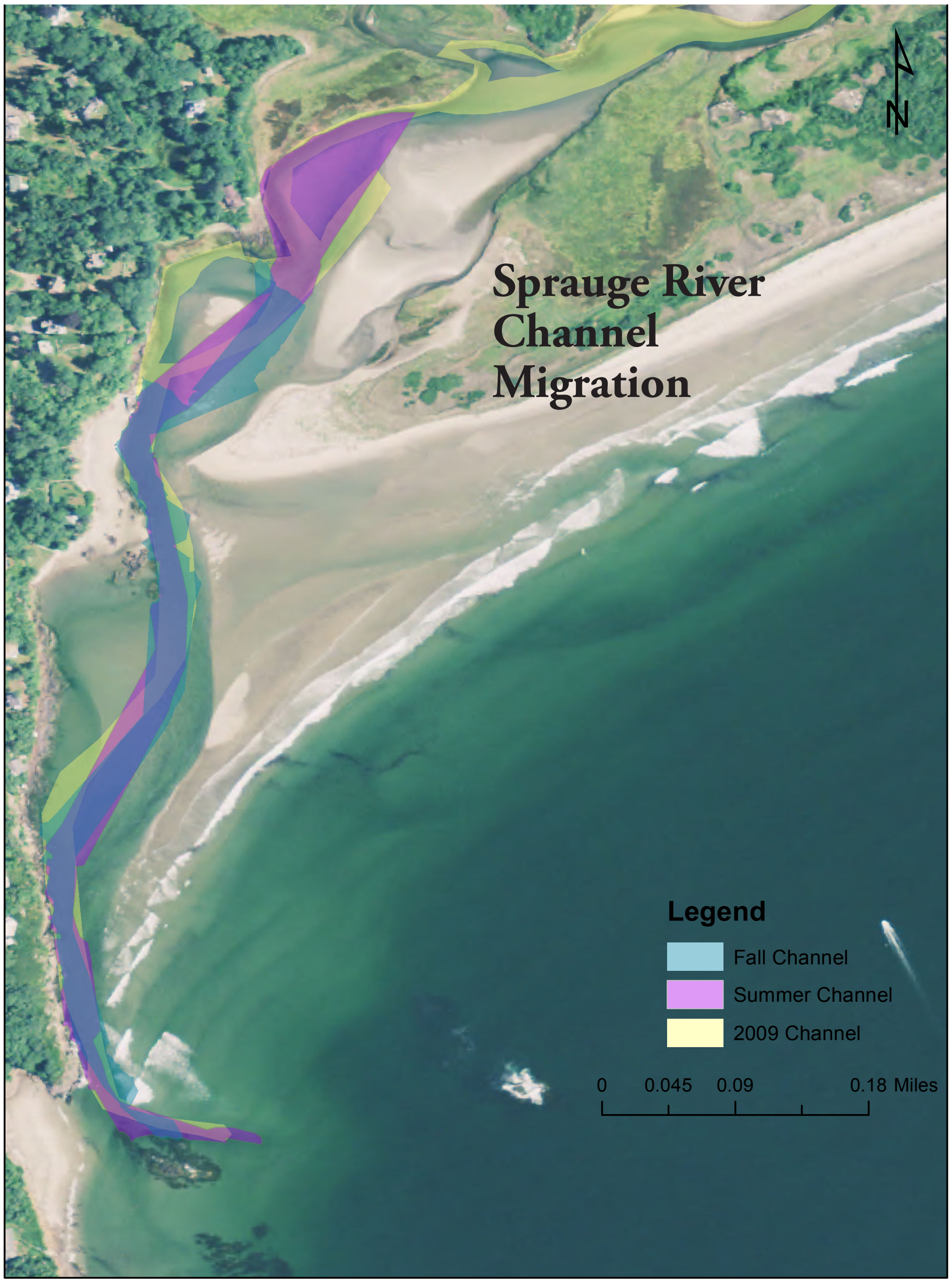


Figure 3.8: GIS image of the low tide channel margins of the Sprauge River Channel. Image depicts short term (seasonal) migration in purple and blue as well as longer term channel migration in yellow. Note how the distal portion of the channel is anchored up against the Cape Small headland by growth of the southwestern Seawall spit (BCIC, 2013)

3.3.2 Seawall Beach

Seasonal changes at the Seawall Beach frontal dune ridge were documented using a GPS tracking system during August 2012 and November 2012, prior to the land fall of Hurricane Sandy and the Winter Storm Athena. Tracks were recorded at the base of the frontal dune scarp and the beginning of the berm scarp, and have been split into Seawall Beach West (Figure 3.9a) Seawall Beach Central (Figure 3.9b) and Seawall Beach East (Figure 3.9c).

Figure 3.9a shows recession of the dune scarp and berm interface along the GPS track from the end of summer to the end of the fall season. Erosion is most obvious along the western most portion of the dune ridge and roughly at transect location W500, where the berm has receded towards the frontal dune ridge.

Figure 3.9b shows less erosion resulting from seasonal weather patterns than did tracks along Seawall West. However, recession of the frontal dune ridge and berm interface occur approximately 300m west of the Morse Mountain Conservation entrance to the barrier beach. Near the location of transect W100 almost no loss or growth has occurred along the dune-berm interface.

Seawall East experienced the most overall erosion compared to any other sector of the barrier beach. Figure 3.9c highlights the bedrock outcrop just east of the conservation walkway onto the barrier beach, in which the fall track begins to curl around the outcrop, with tide action washing away berm features once anchored behind this outcrop as recently as August. Although limited change occurred from summer and throughout the early fall season, the frontal dune ridge as well as the berm scarp are presently located on what used to be back dune vegetation in June of 2011, when the aerial image was taken. This trend continues past transects E100 and E200 to the northern Seawall spit, where minimal erosion occurred to the frontal dune ridge and berm.

Figure 3.9a: Recession of the Seawall Barrier west sector frontal dune ridge from the summer season in black to the fall season in red. Although recession is minor, there is obvious evidence near the right hand portion of the ridge within the image, as well as recession at the proximal end of the southwestern Seawall spit (BCIC, 2013)

Figure 3.9b: Recession of the Seawall central sector frontal dune ridge. This portion of the barrier had the least change occur, however notable recession from summer (black) to fall (red) lines is visible in the left hand portion of the image. This is approximately just left of the location of transect W500. Slight erosion of the dune face is visible on the left hand portion of the image as well, thus little to no erosion has occurred at W500, in between the aforementioned sites (BCIC, 2013)

Figure 3.9c: Recession of the east sector of the Seawall barrier frontal dune ridge. This sector of the barrier experienced the most change in comparison to the west and central sectors of the beach, with summer tracks represented in black and fall tracks represented in pink. There has been notable recession since 2011, year of the orthographic image over which 2012 tracks have been superimposed. (BCIC, 2013).

3.3.3 Morse River

Tracks following the low tide channel banks of the Morse River inlet were documented during late August 2012 and during late fall of December 2012 (Figure 3.10). Yellow tracks denote the channel path in 2009 before the Morse River breached the northwestern Seawall spit in 2010. Since then, the Morse River has continued to follow its 2010 path, shown by the blue and purple tracks. Throughout 2012 the Morse River has enhanced meander features as the channel migrates northeast towards Popham Beach, and away from the northeastern Seawall spit. Fall 2012 channel tracks, shown in purple, show migration of the river mouth west ward where it has since anchored against a bedrock outcrop off of the northwestern Seawall spit.

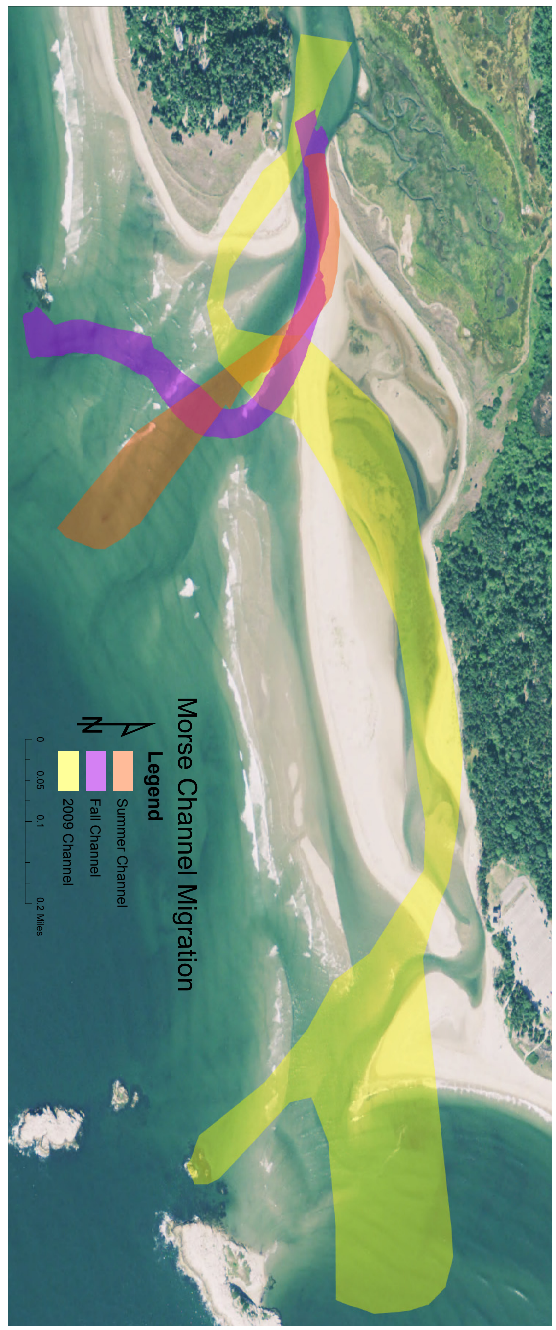


Figure 3.10: Migration of the Morse River Channel since 2009 (yellow). Since 2010 the channel has remained in its current location, however channel traces are still visible on the Popham Barrier (BCIC, 2013).

3.3.4 Popham Beach

Frontal dune ridge location was tracked in late October and early November of 2012 using the high resolution Trimble GPS. Figure 3.11 shows dune migration landward from 2003 to 2012, overlain on the 2012 satellite image. Hurricane Sandy and Athena had minimal influence on recession of the ridge, however visible migration of the dune ridge has occurred since 2010(dark pink line), when breaching of the northwestern Seawall spit occurred. By the West Bath House there is approximately 5 meters between the West Bath House and current high tide mark, a significant loss since 2003 when there was almost 300m of distance between the dune ridge and the current location of the West Bath house, yellow line. Along the northeastern sector of Popham Beach, visible back dune vegetation has been lost as the dune ridge migrated landwards from 2010 to 2012 tracks, dark pink, blue, and purple, respectively. Little to no change has occurred along the southwestern portion of the dune ridge, possibly a result of decreased tidal activity with the migration of the Morse Channel west and away from this area.

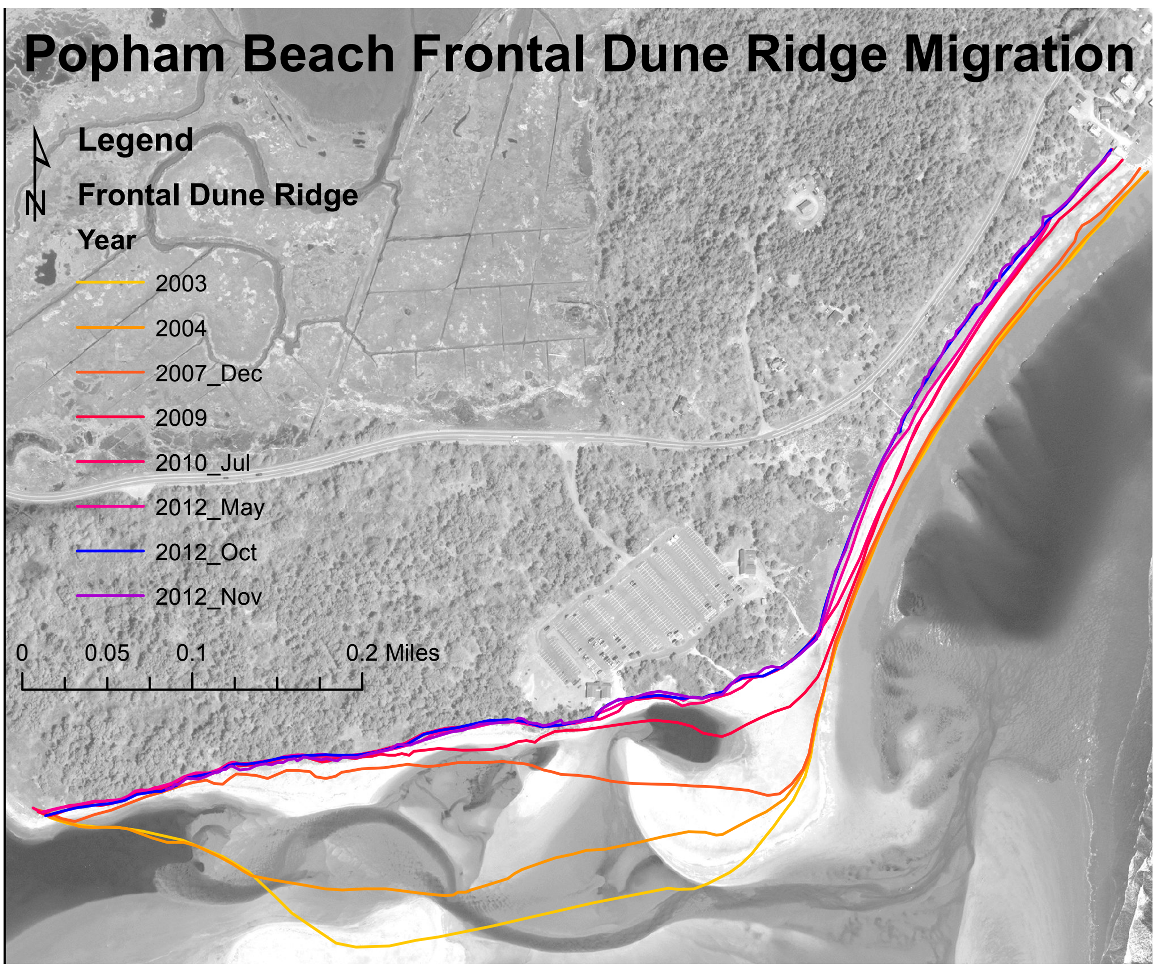


Figure 3.11: Recession of the Popham barrier frontal dune ridge since 2003 (yellow) until present (purple). The current high tide water mark has been observed to be approximately 15 feet from the West bath house, shown above. Visible recession has occurred since 2010, with minimal recession occurring seasonally in 2012 (BCIC, 2013)

3.4 Storm Mobilization of Sediment

As the Hurricane Sandy and the Winter storm Athena had an impact on the Maine Coast, net sediment movement was analyzed at all transects in the complex before and after the storm, using profiles taken pre- and post-storm. Table 3.2 delineates the sediment transport activity of all transects. Transects with both loss and gain along their transect length have been separated and named accordingly. Of the most interest are transects 'W1500 Sandy', in which 2255 m3 of sand was accreted onto the shore face, and 'W1100 Sandy', the nearest transect still on the Seawall barrier, which lost 257 m3 of sand during the storm events. Transect 'W100 Sandy' is of interest as well, as the transect reversed processes after the successive storm events. This is indicated by the 1650 m3 of sandy which accreted to the shore face in comparison to the 1028 m3 of sand which was eroded specifically from the berm during the early fall period.

The pocket beaches adjacent to the Seawall barrier experienced accelerated transport processes during the two storms in comparison to early fall transport processes, with transects IB I, IB II, LB I, and LB II, exhibiting erosion. Transect IB III was the only transect varying from this erosive trend as it the shore face continued to accrete sand both in the early fall period as well as during the storm events.

Unfortunately, transects along Popham Beach were only surveyed before Hurricane Sandy, and therefore sedimentation patterns before and after the storm event cannot be compared, however overall patterns for the early fall period have been included in table 3.2.

Location	Length Analyzed (m)	Sand Vol (m^3)	Erosion	Accretion
E100	13	2849	X	X
E100 Sandy	13	517	X	
E200	25	545	X	
E200 Sandy	35	282	X	
W100 Berm	26	1028	X	
W100 Sandy	26	1650		X
W500 Dune	33	70	X	
W500 Berm	33	772		X
W500 Dune Sandy	33	62	X	
W500 Berm Sandy	33	296		X
W1100 Dune	43	225		X
W1100 Berm	43	105		X
W1100 Berm Sandy	43	258		X
W1500 Dune	52	83	X	
W1500 Berm	52	382	X	
W1500 Sandy	52	2256		X
IB I Berm	13	702		X
IB I Sandy	13	203	X	
IB II	6	3958		X
IB II Sandy	6	1359	X	
IB III	20	1347		X
IB III Sandy	20	1692		X
LB I	20	954		X
LB I Sandy	20	1008	X	
LB II	20	0		
LB II Sandy	20	219	X	
WBH Berm	17	1673	X	
Middle Berm	28	156		X
East Stair	23	690	X	

Table 3.2: Table documenting the volume of sand mobilized seasonally and as a result of Hurricane Sandy and the winter storm Athena, October 28th and November 7th, respectively. Note the massive amount of accretion to transect W1500 associated with the passing of the storm events.

Chapter IV
Discussion

(Wescott, 2012)

4.1 General Beach Response

Seasonal morphology of the barrier complex was segmented into summer, early fall, and late fall periods based on similar sedimentation patterns and processes. However, there are some deviations from the general accretionary or erosional trends even within these periods. Since the seasonality of beach response and sediment transport has been studied before by Chandler (2009) and Schuler (2010), this study attempts to incorporate the influence a large scale storm event would have on previously documented transport patterns during the summer and fall seasons of 2012. Figure 4.1a-g contains a summary of profile data using Kurt Schuler's August 2009 profile data as a baseline. Black lines represent August 2009 data, red lines represent August 2012, Teal represents June 2012, blue represent October 2012 and green represents November 2012, and graphs follow period segmentation of summer, early fall, late fall, as well as August 2009 graphed against August 2012 to create baseline measurements.

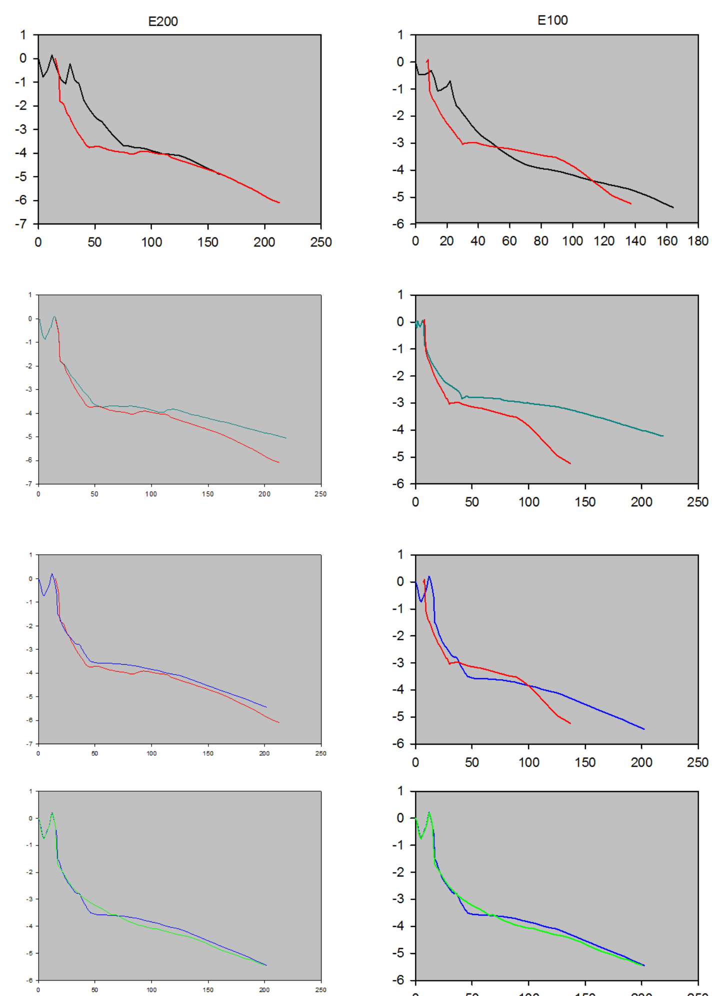


Figure 4.1a: Summary of profile data for E200 and E100. All graphs have elevation change (m) on the y axis and distance (m) on the x axis, 2009 profile data documented during Schuler's 2010 study.

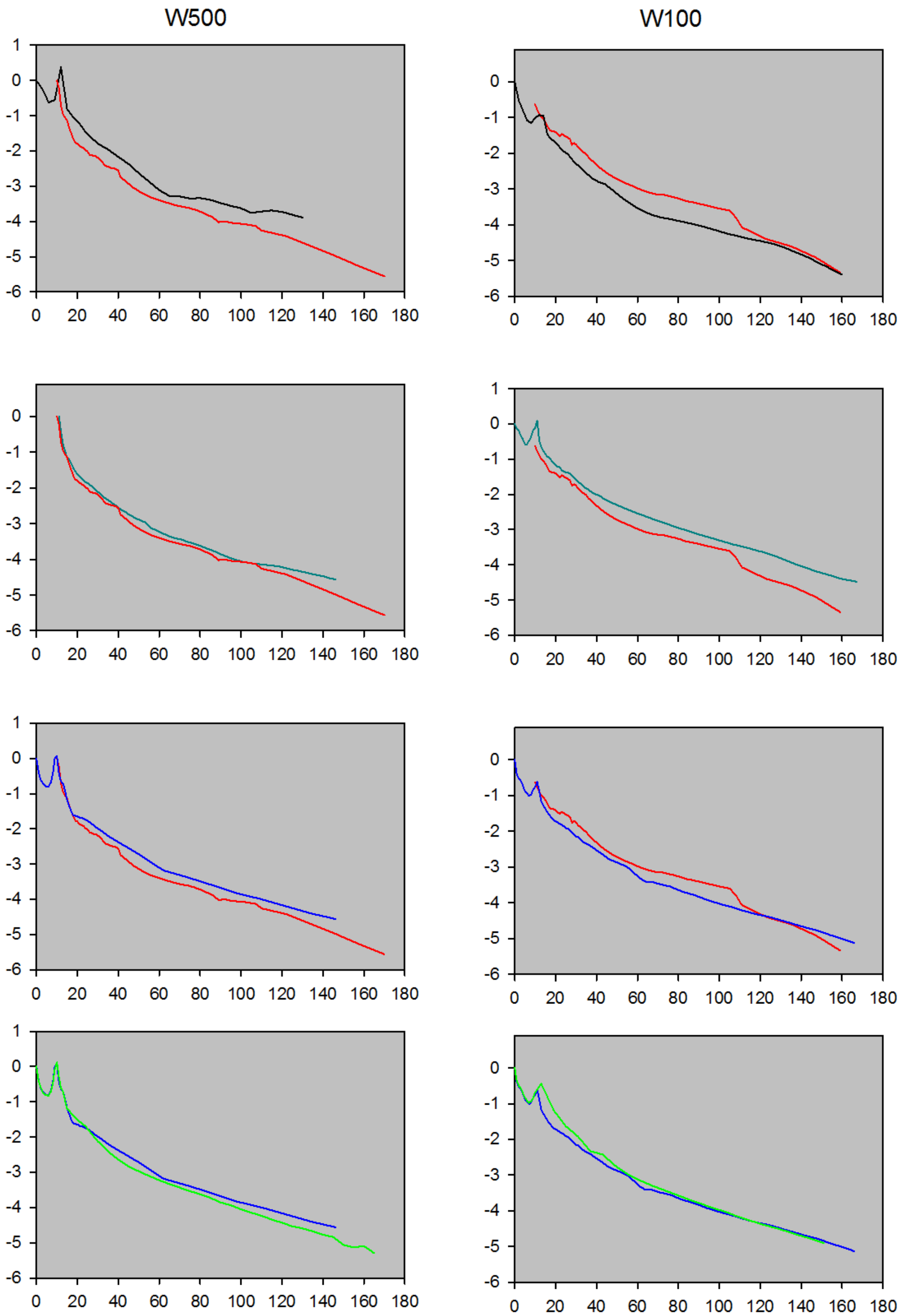


Figure 4.1b: Summary of profile data for W500 and W100. All graphs have elevation change (m) on the y axis and distance (m) on the x axis, 2009 profile data documented during Schuler's 2010 study.

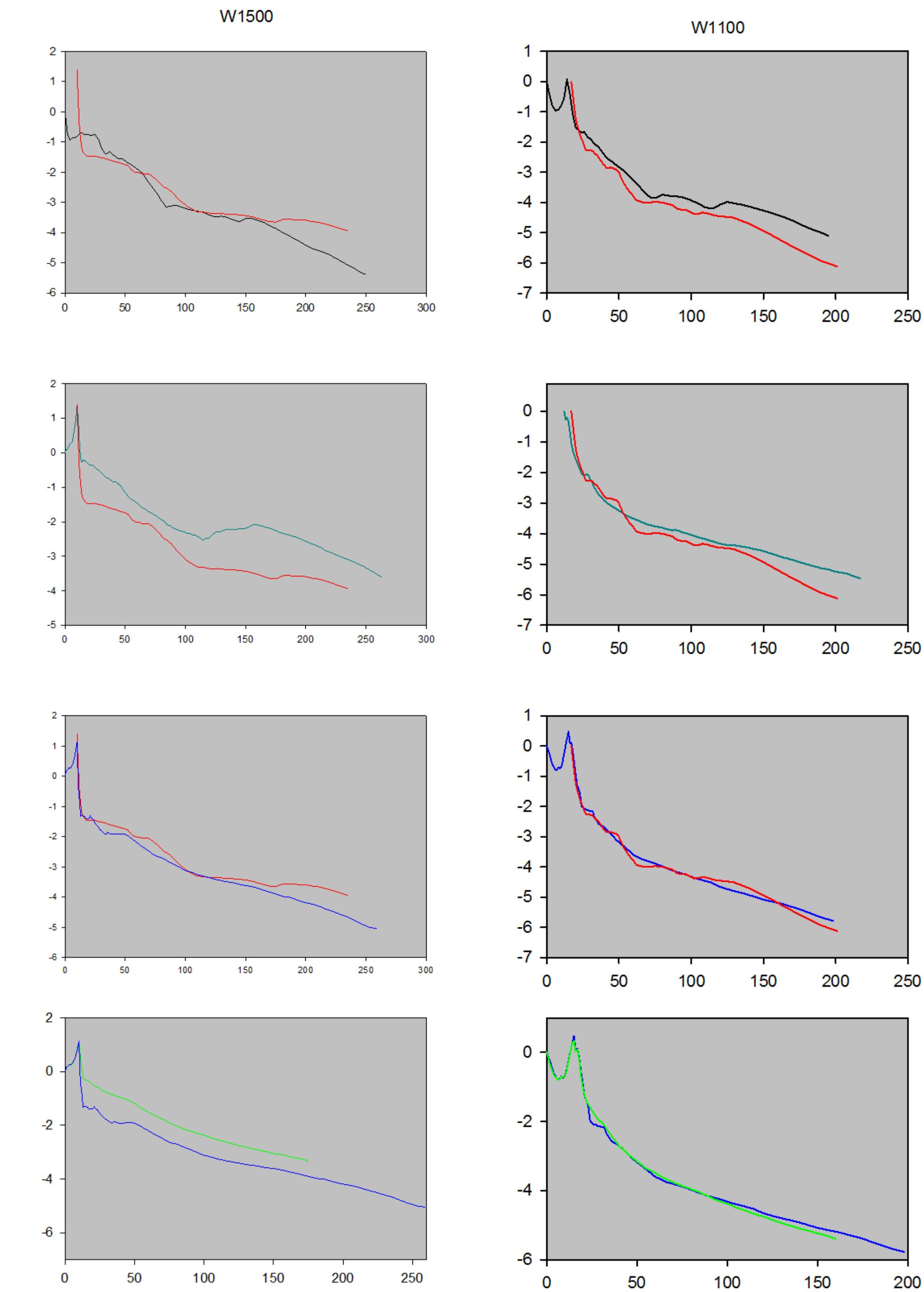


Figure 4.1c: Summary of profile data for W1500 and W1100. All graphs have elevation change (m) on the y axis and distance (m) on the x axis, 2009 profile data documented during Schuler's 2010 study.

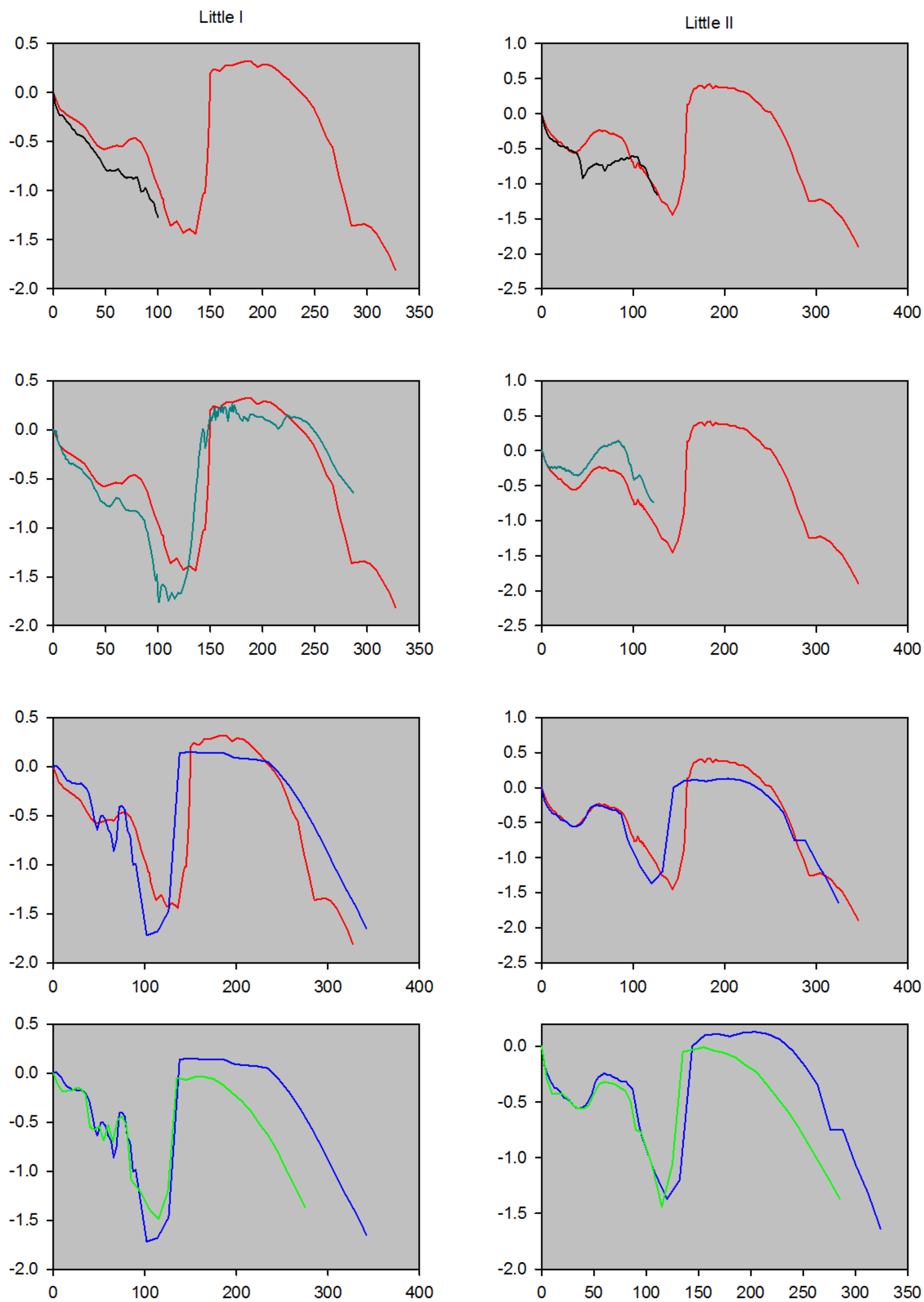


Figure 4.1d Summary of profile data for Little Beach I and II. All graphs have elevation change (m) on the y axis and distance (m) on the x axis, 2009 profile data documented during Schuler's 2010 study.

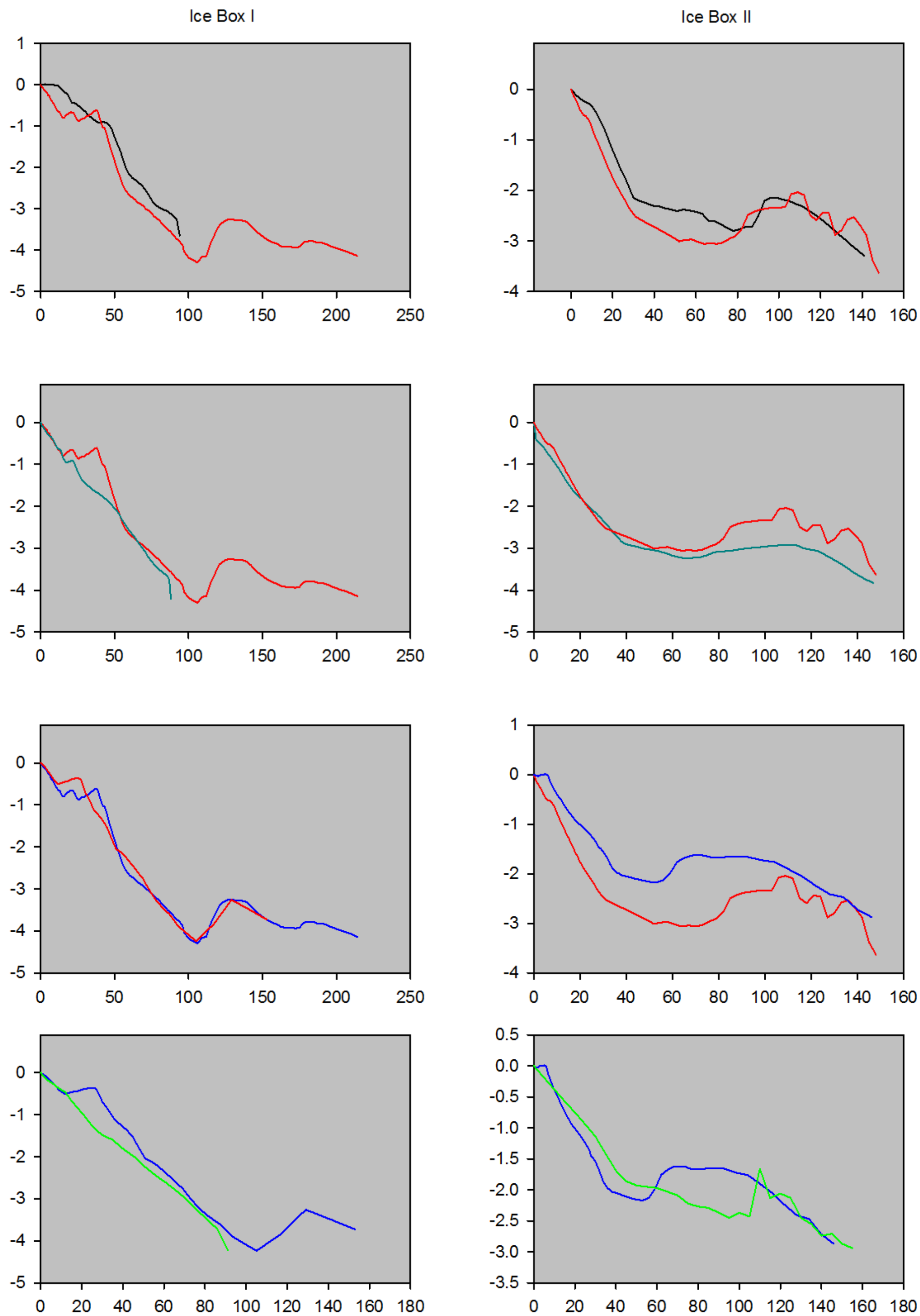


Figure 4.1e: Summary of profile data for Ice Box Beach I and II. All graphs have elevation change (m) on the y axis and distance (m) on the x axis, 2009 profile data documented during Schuler's 2010 study.

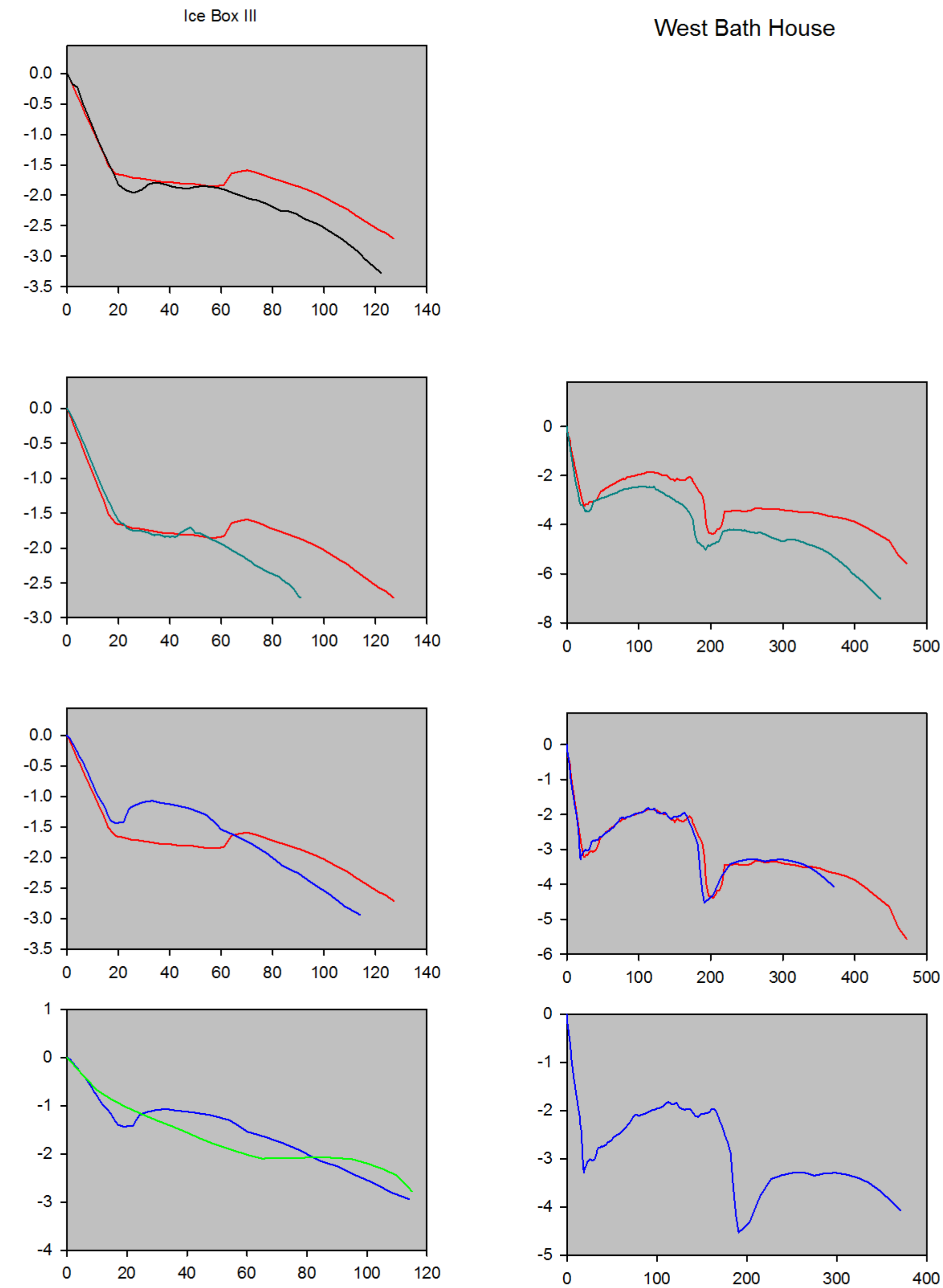


Figure 4.1f: Summary of profile data for Ice Box Beach III and West Bath House. All graphs have elevation change (m) on the y axis and distance (m) on the x axis, 2009 profile data documented during Schuler's 2010 study. Data at Popham Beach was not collected until Summer of 2010 and was not accessible therefore data included begins in June (teal).

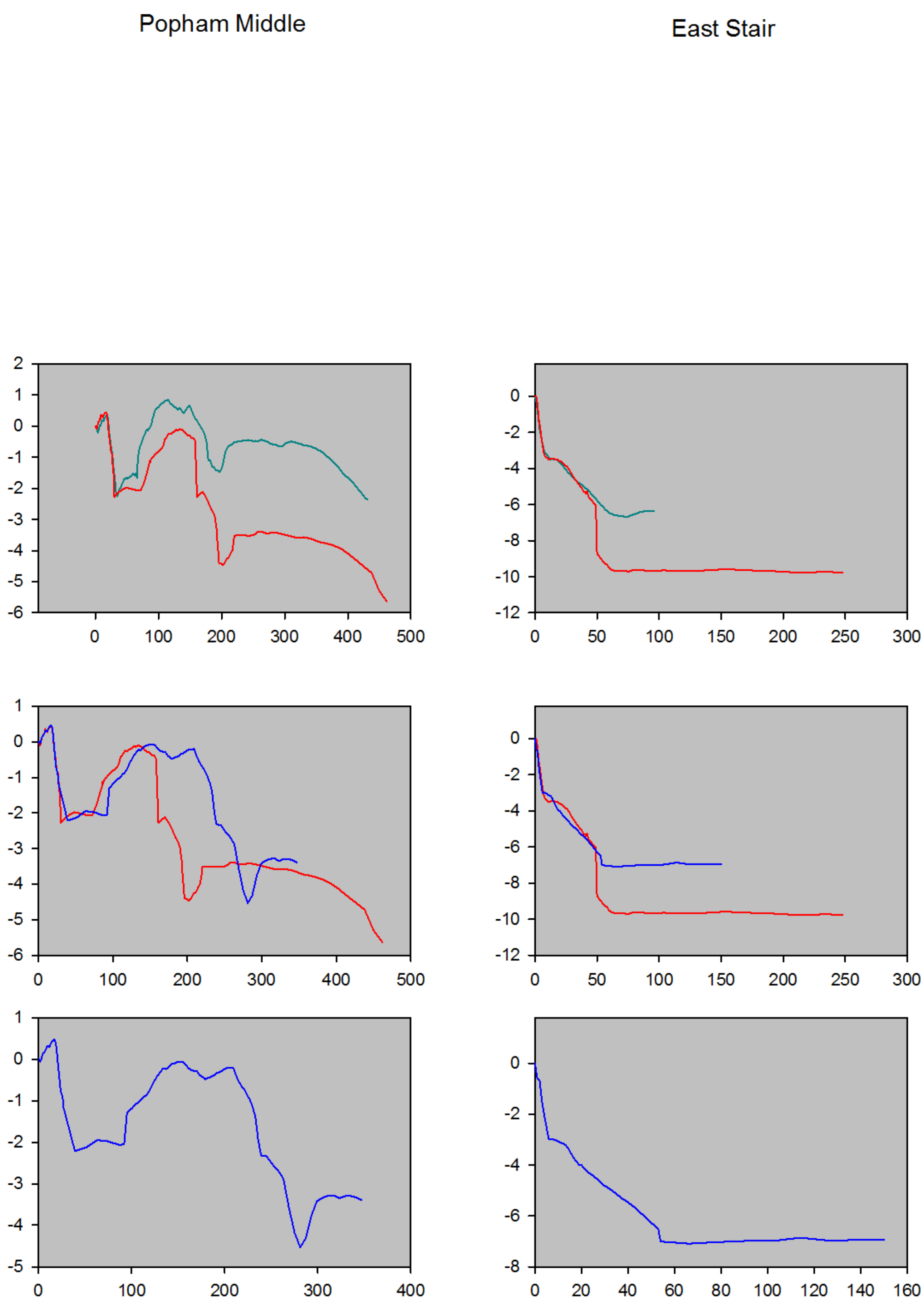


Figure 4.1g: Summary of profile data for Popham Middle and East Stair. All graphs have elevation change (m) on the y axis and distance (m) on the x axis, Popham data was not collected until the summer of 2010, and was not accessible. There for data included begins in June (teal)

4.1.1 Summer

The summer period lasting from June 1st through August 30th, was not as consistent with previous studies or with the expected behavior of barrier complexes during the fair weather summer months (Sverdrup et al., 2005). In both 2009 and 2010 the barrier complex exhibited growth and the development of constructional features from onshore transport of sediments (Hine, 1979). During the 2012 summer period, almost half of the profiles exhibited accretion while the remaining seven exhibited erosive sedimentation patterns.

As shown in table 3.1, only three storms influenced the study zone during this summer period, one reaching severe intensity and one reaching significant intensity as defined by Dolan and Davis (1992). Average wave height for these three storms reached 2.63m and wind speeds averaged at 9.11 m/s, both significantly higher than seasonal averages of .69m and 3.8 m/s, respectively. Although within hurricane season, these massively powerful storms are slightly uncharacteristic of the summer season, characterized by fair weather trends and low energy waves that build up the berm, thus generating a constructive profile (Morisawa and King, 1974). However, profiles from the period do not specifically exhibit a stereotypical constructional profile. Instead, most profiles have a flattened beach face with only a slight berm. This can be attributed to the powerful storm activity dominating the first few weeks of this summer period. These storms enhanced long-shore westward sediment transport, supported by continued growth of the southwestern Seawall spit, the terminus of long shore transport (Hine, 1979) as well as by slight accretion to the frontal dune ridges of E100 and E200 (Figure 4.1a). Growth of the southwestern spit explains erosive trends along the pocket beaches on the western edge of the spit. Since westward long shore transport terminates at the eastern bank of the spit; sand cannot accumulate on the berm of these beaches. Instead, derived sediment is incorporated into the growing spit itself, enhancing erosional effects on the pocket beaches from the Sprague River channel, to be discussed later.

Storm activity in conjunction with wave refraction, a theory expanded on by Carey (2005), induces long shore transport which increases sediment transport within the system. The described storm waves and winds had intensity levels which theoretically, could have been responsible for erosion of sand from the shore face and berm thus resulting in the late June profile shape observed (Figure 4.1a-g). Other possibilities such as variations in sediment supply could influence profile shape. Dredging of the Kennebec River on September 1st, 2011 (USACE, 2011) influences sediment supply, as dredged sands are deposited offshore and within the estuary mouth (Fenster et al. 1996). Although some of the sediment is deposited within the Kennebec sediment gyre, there is a significant loss of sediment from the system, as 47,900 m47, 900 m^3 of sand is deposited off shore and thus not immediately incorporated back into the barriers (Fenster et al., 1996).

Since transects along Popham Beach are a relatively new addition to the project, little data is available for comparison. However, in the summer 2012 off shore bars welding onto the low tide terrace of the West Bath House transect is noticeable (Figure 4.1f). This ridge-runnel development at the West Bath House profile, caused by landward-migrating intertidal swash bars welding onto the beach face (Hine, 1979) generates a gently dipping summer profile as the bar is incorporated into the beach face and berm. Although some profiles, such as E100, E200 (4.1a), and the West Bath House transects did develop features consistent with characteristic summer processes, constructional profiles were never able to fully develop at the study site, presumably as a result of intense storm impacts. As the severe storm on the 2nd of June and the significant storm on the 18th of June both occurred before surveys were conducted, there is no documented evidence of erosion related to storm influence. However as profiles stray from expected constructional profiles, either storm activity or changes in sediment supply via dredging may be responsible for observed variations in the profile shape from the summer period.

4.1.2 Early Fall

Sedimentation trends are more consistent with usual fall trends as the barrier complex experiences overall erosion other than at profiles E200 and W500 (Figure 4.1a-b). Berm activity strays from this trend as slight accretion occurs at E100 (Figure 4.1a). Otherwise sedimentation along the main Popham-Seawall barrier consists of erosion or minimal to no change. Pocket beaches, Little Beach and Ice Box Beach (Figure 4.1d-f) vary slightly from overall trends, as recreational beach front experiences growth during this transition period of August through October of 2012, rather than beach loss.

Normally all beach faces are beginning to resemble winter profiles as storm frequency increases during the early fall months. September is considered the most active month in terms of storm frequency (Dorst, 2010). However only two storms influenced the study zone during September (Table 3.1) and both were classified as weak category storms influencing the coast (Dolan and Davis, 1992). In contrast, studies conducted by Chandler in 2009 show continued accretionary sedimentation, despite eight storms occurring in the early fall period. This trend lasted through September 21st, 2008, when a significant storm (Dolan and Davis, 1992) initiated a more traditional erosional trend. In the 2010 study conducted by Kurt Schuler, only one storm made landfall in September, causing the barrier complex to maintain accretionary sedimentation through September, similar to the 2009 patterns. This trend ended by October of 2009 with five storms, three of which were powerful enough to generate stereotypical high energy 'destructive waves' (Morisawa and King, 1974) and induce erosional patterns along the complex. As described, storm activity was at a minimum in September of 2012; however this trend was thwarted by the seven storms which occurred in the month of October. Three storms reached moderate, significant, and extreme classifications, while the rest were classified as weak storms, and did not influence sedimentation trends significantly (Table 3.1).

As October transects were measured before Hurricane Sandy hit on October 28th, erosional patterns for the early fall season are attributed to seasonal increases in the hydraulic regime rather than specifically storm activity. From summer to early fall wind speeds increased by 1.85 m/s to 5.66 m/s, while wave heights increased by 3.61 m to 7.11m on average. With this increase in overall storm intensity or power is an increased tendency for effective mobilization of sands via wave action. Thus, sediment is actively eroded from the berm during spring high tides and redistributed along the beach face, or deposited in off shore swash-aligned bars (Figure 4.2) (FitzGerald, et al., 1989). Furthermore, the increase in storm activity, despite class, allows consistently stronger wind speeds and waves, producing an increase in water level (Zhang et al., 2002) particularly when coinciding with spring tides. This allows maximum erosion potential on the beach face. These more active weather patterns are represented by the smoothed beach profiles in October, and illustrate the movement of sediment within the system off shore from the beach face and berm features. In conclusion, the exhibited erosion is a consequence of storm enhanced long shore sediment transport, and is highly characteristic of high intensity hydraulic regime conditions.

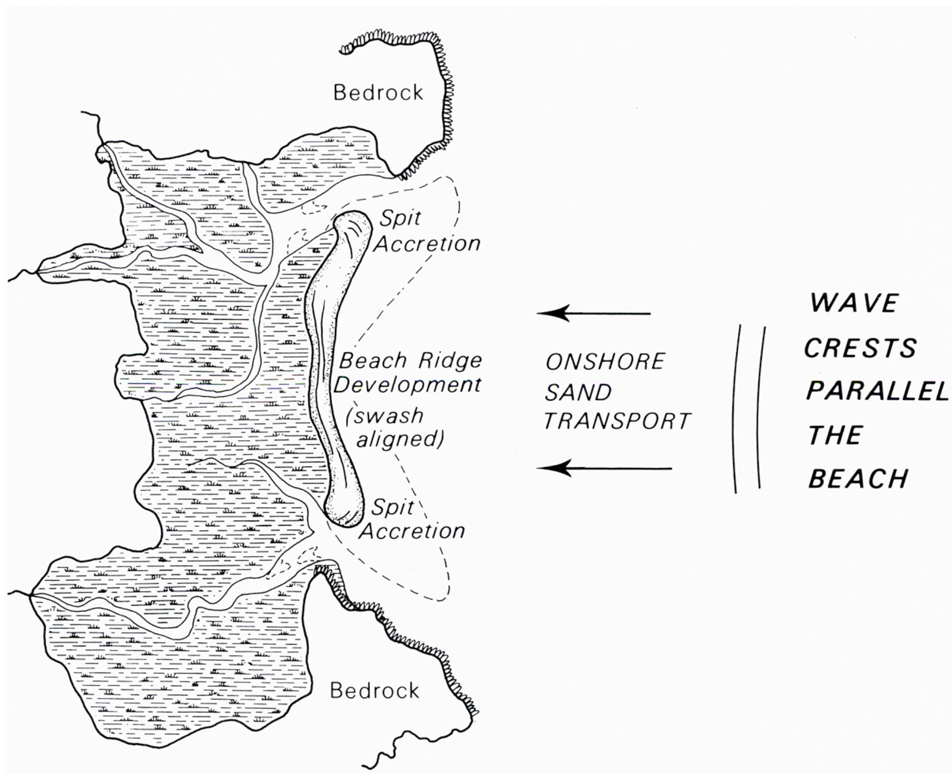


Figure 4.2: Development of off shore swash aligned bars which migrate landward, and eventually weld onto the beach face, and are reworked into the beach system through wave action thus replenishing the barrier. Sand may be stored for 6-9 years in these off shore bars before welding back onto the complex if storm activity is intense enough to erode sand and deposit it off shore (FitzGerald et al., 1989).

4.1.3 Late Fall

The late fall period lasting from October - November of 2012 documented the effects of Hurricane Sandy and the Winter Storm Athena, as well as 5 other storm events (Table 3.1). As described in the results chapter, Hurricane Sandy was an extreme class storm with a total power of 5105.76 (m^2*h) as defined by Dolan and Davis (1992) with average wind speeds of 8.69 (m/s) and average wave heights of 2.58m. Although average wave heights are not exceptionally large, the storm coincided with spring tides, causing increased wave height capacity and associated wave energy over its 101 hour duration. The maximum wave height reached 7.11m during the event, significantly larger than the late fall average wave height of 1.06m. Although wave direction was not recorded, wind direction was documented as approaching from the southeast direction or 133 degrees. Furthermore it is common knowledge that Hurricane Sandy grounded in New Jersey, tracking north up the coast and ultimately, inland (Drye, 2012). Assuming that the storm approached the study zone from a south to southwesterly direction (Figure 4.3), associated waves and winds would not have generated the necessary long shore transport currents for extensive erosion of sands (Morisawa and King, 1974). Rather, upwelling and transport of sediment onshore, inducing beach growth could have occurred (Hill et al., 2004). However, within two weeks of Hurricane Sandy terminating, the Winter Storm Athena moved over New England on November 7th 2012 and lasted another 42 hours. The Winter Storm Athena had a total power of 1496.92 m^2*h, and maximum wave heights of 5.97m, but coincided with neap tidal swells therefore reducing the storms overall erosive capacity. This storm approached from the northeast, as described by a documented average wind direction of 74 degrees (Table 3.1), thus it is assumed that waves approached the complex from a northeast direction as well. Morisawa and King (1974) point out that waves which approach the beach at an oblique angle enhance long shore currents and sediment transport. In this specific study zone storm systems approaching from a northeast direction approach the complex at an oblique angle, thus increasing long shore currents as suggested. Therefore the Winter Storm Athena, despite the storms low power and erosive potential, increased long shore currents. It is important to understand that these two major storm events hit land within such a short period of time that the beach complex was not able to fully recuperate from Hurricane Sandy's initial impacts. Therefore the combined influence of both storms caused amplified amounts of sand transport as a result of the preconditioning of the beach system.

The increase in sand movement over this period is visible in profile W1500 (Figure 4.1c), which experienced over 2256 m^3 net accretion of sand between October 29th and November 18th, of 2012. The W1500 profile is located adjacent to the southwestern Seawall spit, where net accretion occurs on the spit if sand is not lost to offshore bars. At the western end of Seawall Beach, this transect receives all mobilized sand from the long shore current along the Seawall Barrier. Profiles W500 and W1100 exhibit minor accretion (Figure 4.1b-c), a total of 296 m^3 and 257 m^3 to the berm (Table 3.2). This can be explained by the wave corridor theory (Carey, 2005) which suggests wave corridors located perpendicular to W500 and W1100 (Figure 4.4) that enhance transport of sediments found in the swash aligned bar systems (FitzGerald et al., 1989 and Kelley et al., 1993). Therefore, under the

Figure 4.3: Hurricane Sandy hitting the New Jersey and New York coastlines on October 29th, 2012. Storm track is visibly moving north-north east up the coastline, therefore approaching the study zone from a southwest direction which can induce upwelling along the Maine coastline. Image modified from Dyre (2012)

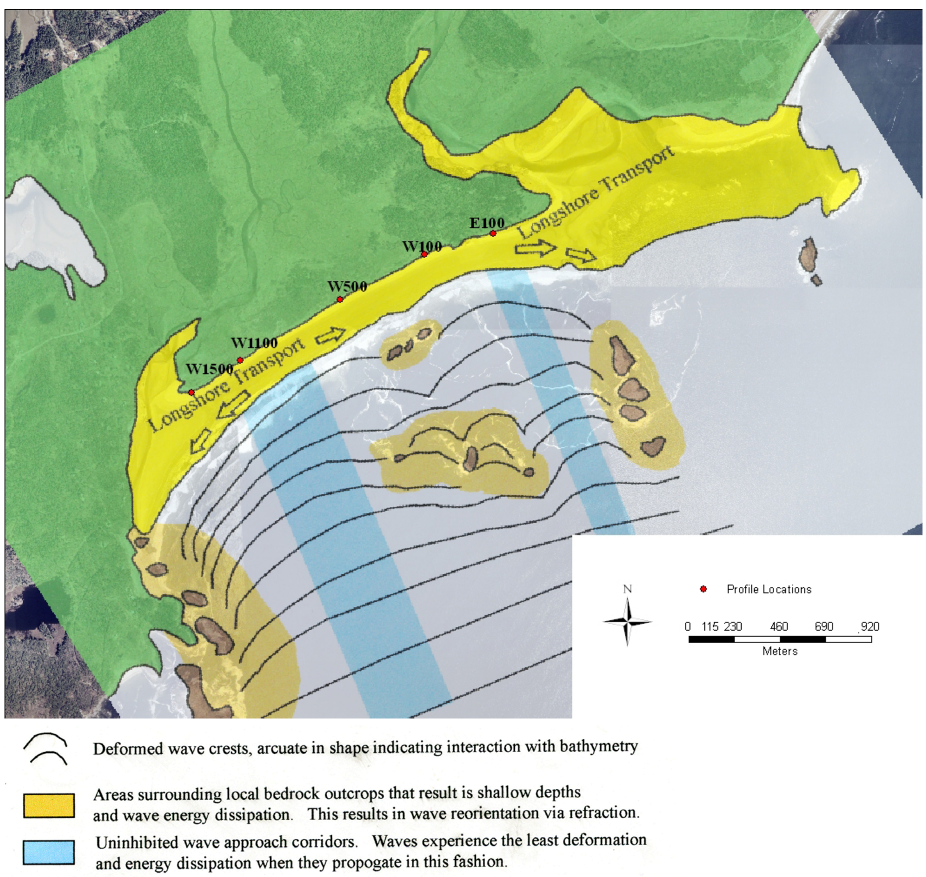


Figure 4.4: Image modified from Carey (2005) showing wave corridors inducing wave refraction that enhances sediment transport of swash aligned bars welding onto the low tide terrace as proposed by FitzGerald et al. (2000).

specified storm conditions present in Hurricane Sandy and the Winter Storm Athena, a southwesterly approaching storm and a low power neap tidal storm, respectively, accretion via wave action working off shore deposits onto the beach face is plausible, even under storm conditions. Hill et al. (2004) shed evidence that storm activities are a complex process, and are responsible for reworking sediment onto the beach and rebuilding it, as well as causing beach loss. Furthermore Stone et al. (2004) found that weaker hurricanes such as Hurricane Danny and Hurricane Georges (and in this study Hurricane Sandy), can rework considerable amounts of sediment to the berm and relict over wash terrace. Sand transport via erosion is also visible at profiles, E100 and E200 (Figure 4.1a), however this sector of the beach has exhibited consistent rates of erosion throughout the early fall season. Therefore the continued erosion could be a result of enhanced long shore transport of old established currents during the storm events.

In comparison to transects from the 2010 studies, the late fall period experienced overall accretion, which is a deviation from the usual destructive trends accompanying increased storm activity during this season. Nine storms passed through the study site within two months while only five total storms in two months affected the study zone in the 2012 late fall period. However, in 2010, six of the nine storms lacked conditions conducive for significant erosion along the barrier complex, whereas in 2012 at least two of the five storms had enough power to induce sand mobilization throughout the beach complex. This variation in storm compatibility can be linked back to the ENSO cycle. During the 2012 late fall period, the ENSO cycle was in an El Niño neutral phase (NOAA, 2013), a phase recognized for increased hurricane potential (Bove, 1998). In contrast the ENSO cycle was in an El Niño positive phase during previous studies conducted in 2008-2010, therefore reducing hurricane potential and strength (Bove, 1998). Although 2010 saw higher frequencies of storm activity, none of the storms had the combined impact of Hurricane Sandy and the Winter Storm Athena.

4.2 Storm Influence and Sea Level Rise

Storm activity on the Popham - Seawall barrier complex illustrates how effective storm events are at inducing mobilization of sediment throughout a complex, whether trends are constructional or destructive. Many studies have been conducted along the eastern coast of the US as well as internationally in an attempt to decipher the implications of major storm events on beach equilibrium and sediment cycling (Stone et al., 2004, Cooper and Navas, 2004, Cooper et al., 2007, Morton et al., 1995, and Zhang et al., 2002).

Zhang et al. (2002) determined that beaches recover after storm events to positions consistent with long term or 100+ year trends along the eastern US seaboard. However, Zhang et al. (2002) focused their research on barrier beaches in which no local inlet interaction is incorporated, as this often influences long shore sediment transport in conjunction with storm activity, complicating the system. In terms of the Popham - Seawall barrier complex, this finding may not be entirely accurate as there are two individual inlet systems within the barrier complex. The Sprague River channel and the Morse River channel are both active, migratory, and tidally influenced river channels which play a large role in sediment circulation between the off shore, near shore, and backshore zones of the barrier complex. All the same, Zhang et al. (2002) findings should be considered as it is important to understand why barriers islands, specifically along the Atlantic and Gulf Coasts migrate continuously landward in relation to sea level rise and storm activity (Leatherman, 1982).

Air photograph analysis that began in 1953 shows that the Sprague River channel, as discussed by Chandler (2009) and Schuler (2010), migrates between its eastern most position crosscutting the southwestern seawall spit, to its western most location anchored against the Cape Small headland (Figure 4.5). Currently, the channel is anchored against the headland, and has been so since 2001, as seen in Figure 4.5b. Images from 1966 show the channel in its eastern most location (Figure 4.1a). The location of the channel is related to long shore transport patterns along the Seawall barrier, and thus southwestern spit growth. As growth of the spit is assumed to result from westward long shore transport of barrier sediment via oblique wave action, a higher frequency of northeast storms must occur to maintain spit growth, anchoring the Sprague River channel against the headland. Hill et al. (2004) found that northeast storms were the only events that could cause significant beach sand loss, and in turn mobilize sediment for continued growth of the spit. Recent Nor'easters, including the Winter Storm Athena during this study session, have provided powerful enough winds and waves which induce this long shore transport, build the southwestern spit, and essentially lock the Sprague River channel into its current location causing massive erosion to the recreational beach front of Ice Box Beach and Little Beach.

Figure 4.5a-d: a, migration of the Sprague River channel between its extreme northeast location in 1953, b: channel in a neutral location in 1966, c: in 1997 the channel seems to have migrated towards its northeastern extent and, d: the channel is in its extreme southwest location anchored against the Cape Small headland (images modified from Bates Geology Department, 2013).

The Patriot's Day Storm, of April 15th, 2007, is another prime example of powerful Nor'easters which generate long shore transport and allow growth of the southwestern Seawall barrier spit. Wave buoys recorded the maximum wave heights, ever, during the Patriots Day storm, which also exceeded the 100 year return period of a storm (Marronne, 2008). These wave heights reached 10m (Maronne, 2008), and as they approached from a northeast direction, generated intense long shore transport currents. These beach-derived sediments accumulated on the spit, and continued westward growth both vertically and laterally in 2007, helping to anchor the Sprague Channel against the Cape Small headland. Furthermore, Schuler in 2010 documented a powerful storm on November 14th of 2009, which approached from a northeast direction, and increased westward growth of the spit via long shore transport of eroded barrier sediment. The Patriot's Day Storm also induced morphological changes to the Morse River Channel inlet, and changes along the frontal dune ridge at Popham Beach (Figure 3.11).

In 2007, the Morse River channel migrated in a northerly direction as a result of influence from the Patriots Day Storm. From 2007 to 2011, accelerated erosion of the Popham Beach State Park beach front is visible (Figure 4.6), and is a function of tidal influence from the Morse River channel and approach of storm waves through a major gap between the eastern end of the Seawall spit and Fox Island. In 2010, Schuler documented avulsion of the northeastern Seawall spit by the Morse River (Figure 4.7), allowing the channel to relocate to its position represented by yellow tracks seen in Figure 3.10. Since 2009, the Morse River channel has remained roughly in this same orientation, with 2012 seasonal migration shown in orange and purple (Figure 3.10). Development of a northward migrating meander is visible in the fall tracks, shown in purple. Meander development insinuates decreased flow velocity within the channel, as well as sediment deposition and thus in fill as velocity decreases and suspended and bed load cannot be supported. Morton et al. (1995) point out how tidal inlets have the ability to interrupt, temporarily or permanently, long shore transport through various processes causing sand storage, specifically if sand accumulates on flood or ebb tidal deltas. In this case, meander development is related to growth of the northeastern Seawall spit through eastern long shore transport depositing sand at the distal portion of the spit (FitzGerald, 1989) although erosion and migration landward of the frontal dune ridge are visible in figures (3.9a-c). As growth of the spit forces the migration of the Morse River meander north-northeast, dissection of the northeastern Seawall barrier spit beings to occur, in turn generating an off shore sediment bar east of the channel (4.8c). Here, lateral accretion on the up-drift side of the inlet enhances the detached spit or sand bar feature (Morton et al., 1995). Normally, swash aligned and offshore sand bars, (Figure 4.4c), migrate across the low tide terrace and weld onto the existing berm (Hine, 1979). Welding replenishes the beach face, allowing for equilibration to pre-storm conditions. This process occurs where onshore transport rates are high (Hine 1979). However, the old Morse River channel running east-west across the State Park Beach front is still tidally active, therefore preventing sustained on-shore transport of sediment to the recreational beach and equilibration. With continued prevention of onshore transport by the Morse River channel, the off-shore sand bar may well develop into an isolated barrier island, depleting the recreational beach further. This is especially feasible if the Morse River channel regresses to its pre 2010 location (Figure 4.4a-b), which will enhance tidal activity and erosive trends along the State Park Beach front. Furthermore this theory is supported by evidence from Morton et al. (1995) who conducted a study on coastal Texas, which proved that cycles of

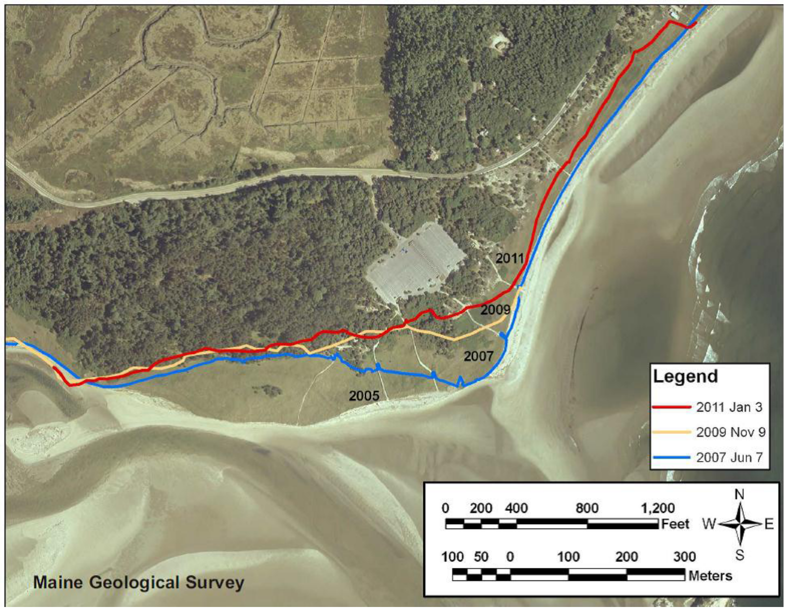


Figure 4.6: Erosion at Popham Beach State park, in which migration of the Morse River Channel Northeast in 2007 caused accelerated erosion of the frontal dune ridge and berm (Image modified from Dickson, 2011).

Figure 4.7: Avulsion of the northeastern Seawall barrier spit by the Morse River in 2010 (Image modified from Schuler, 2010)

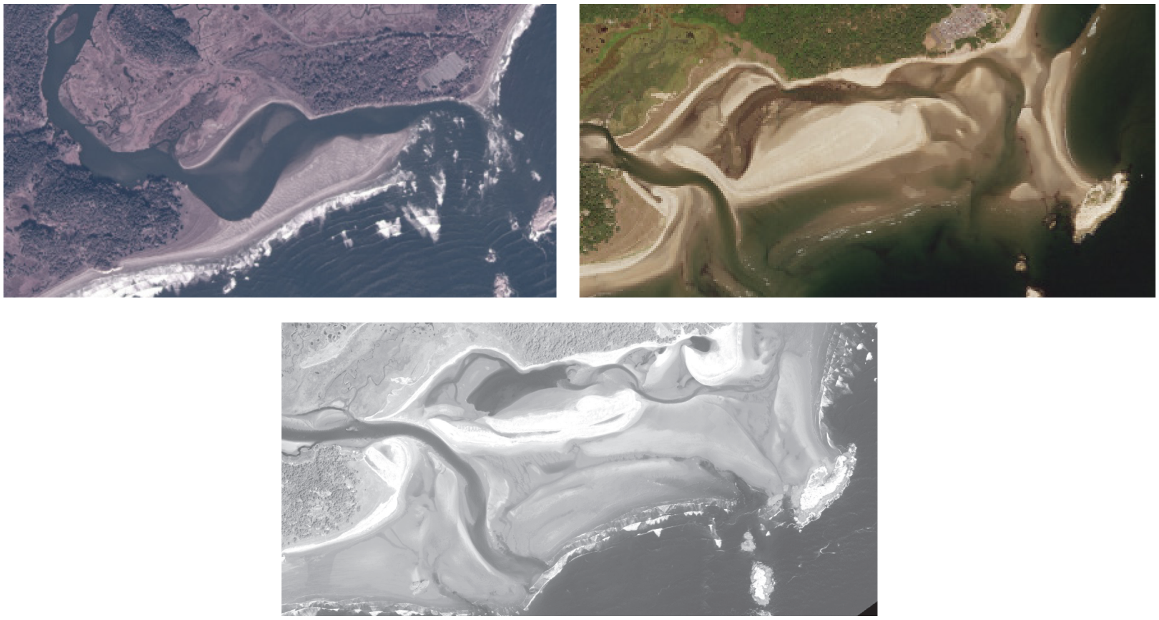


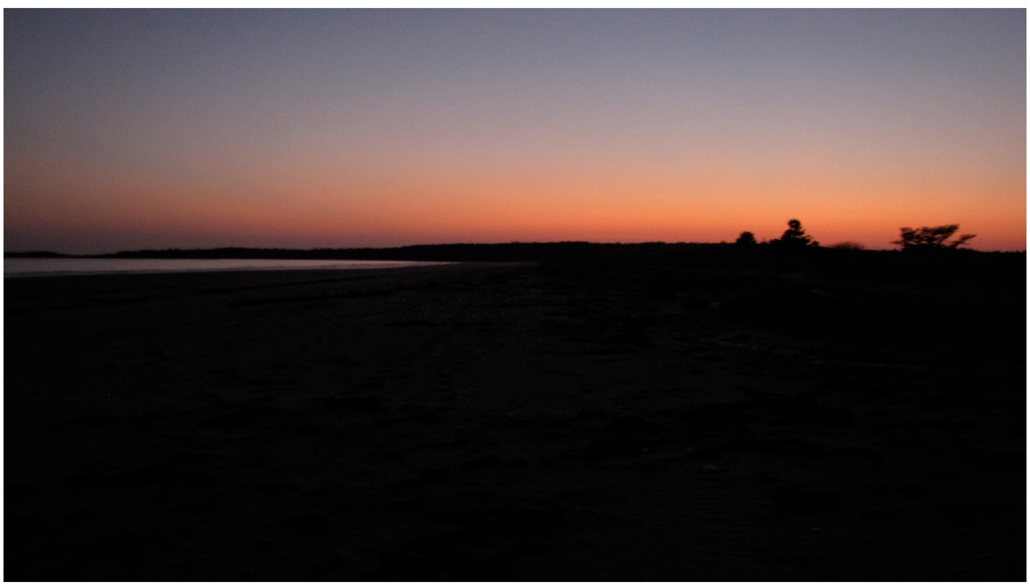
Figure 4.8a-c: a: 2009 satellite image of the Morse River Channel. Note extended Seawall Spit. b: 2010 image post denoting new location of Morse River Channel, as the channel has breached the northeastern Seawall spit by avulsion, an offshore sediment bar was created when breaching occurred. Note that the old Morse River channel is still tidally active. c: 2012 image denoting Morse River location remains consistent with its 2010 position other than some seasonal migration. The separated spit has still not migrated and welded back onto Popham Beach, preventing possible replenishment of the beach face over two years after the Morse River breached the spit. (Image modified from Quickbird Satellite Imagery courtesy of the BCIC, 2013).

rapid, large-scale beach erosion and deposition are typically related to shoal and spit processes involving ebb-tidal deltas and inlet morphology.

Morton et al. (1995) found that tidal inlets and ebb-tidal deltas have localized influence on shoreline change and sediment transport that is dependent on channel position. The Galveston, TX study site is similar to this study zone as long stretches of barrier beach islands are investigated. When the Sprague River channel is at its western- most position, pocket beaches experience extensive erosion while the southwestern Seawall spit growth is enhanced. Migratory bar systems, which are affected by altered wave conditions, effect sediment supply and profile shape, however a relative rise in sea level in conjunction with reduced sediment supply causes overall retreat in the Texas barrier beaches (Morton et al., 1995). Studies show that this retreat is most noticeable at either end of the barrier system, whereas the middle of the system is most stable (Morton et al., 1995). This is similar to the study zone in which sand mobilization causes the most extensive changes to occur at the southwestern and northeastern Seawall spits while W500 (Figure 4.1), essentially the center of the barrier complex, exhibits little change, other than slight accretion, throughout the study period. Although Morton et al. (1995) showed morphological changes related to variations in sediment supply and storm activity, Cooper et al. (2007) describe a cyclicity in geomorphologic change of a barrier beach on the north and west coasts of Ireland that is independent of external factors such as sediment supply, storm activity, and sea level rise. However, it is common knowledge that eustatic sea level rise associated with global warming is occurring as well as increased storm frequency; therefore beaches with constant sediment supply cannot exists at equilibrium. At the Ireland study site in Cooper et al. (2007) a sediment gyre between the ebb-tidal delta, the beach-dune system, and the back barrier estuary exists in which location of the ebb-tidal delta migrating north-south, while abandoned deltas act as sediment sinks for down-drift depleted barrier segments. In this fashion, pocket beaches in the system are cyclically nourished while welding of off-shore swash bars build the affected dune ridge along the main barrier (Cooper et al., 2007). This sediment circulation resembles that of the Morse River channel and Popham Beach. As migration northeast of the Morse River isolates the barrier island from the northeast Seawall spit, the bar can migrate north and in turn weld onto Popham beach. However in recent years there has not been a total switch of channel locations from 2010-2012 (Figure 4.8b-c) further blocking onshore transport, therefore erosive trends remain along the Popham berm, and replenishment is not possible. In contrast to sea level rise as a forcing on geomorphological changes to barrier complexes, a study completed off the southeast coast of Ireland shows that sea level rise is not the driving force of changes in sedimentation patterns (Cooper and Navas, 2004). Rather, changes in the ocean basin bathymetry at a centennial time scale influence wave refraction and transport patterns, ultimately altering shoreline shape (Cooper and Navas, 2004). Observed spit growth and recession landward of high tide water marks and dune ridges are all manifestations of the bathymetry of the study zone. Although development of these same geomorphic changes exists at the Popham-Seawall complex, bathymetric data has not been researched in relation to this study and therefore attributing the geomorphology to such features is not an option.

Dubois (1990) studied shoreline changes in states along the U.S. east coast and found that wave and current actions are the dominant forcing on shoreline erosion in conjunction with rising sea levels. Dickinson (2013) reports mean sea level rise from the Portland tide gauge at a rate of 1.82 mm/yr +/- .11 mm/yr, which is relatively consistent with global rates of 2.4 mm/yr (Stone et al., 2004), while the IPCC (2007) reports global mean sea level rise rates of 1.7 mm +/-.5 mm/yr, with a decadal rate from 1993- 2003 of 3.1+/- .7 mm/yr. That being said, storms of large magnitude and low frequency are recognized for their ability to drive barrier beaches upward and landward, however consistent migration landward of shorelines occurs during calm weather conditions (Dubois, 1990). This signifies two things: (1) sediment is not conserved entirely within the system, and (2) the lack of sand conservation can be related to sea level rise as erosive trends prevail despite minimal storm activity, causing variations to sediment supply. Morton et al. (1995) found that barrier islands actually conserve mass as long as storm frequency does not exceed beach recovery period. However Morton et al. (1995) also point out that conservation of barrier mass cannot be maintained under current conditions of sea level rise coupled with increased high frequency storm activity. Therefore alterations by storm activity, although considered the most significant factor affecting shoreline migration (Stone et al., 2004) is enhanced through sea level rise, which ultimately prevents equilibration of barriers to long-term trend positions (Zhang et al., 2002).

Chapter V
Conclusions



(Lauden, 2012)

5.1 Conclusions

This study set out to determine what effects large scale storm events have on documented sedimentation patterns along the Popham-Seawall Barrier Beach complex back in June of 2012. Unexpectedly, summer profile data showed no over arching sedimentation trends. In fact, almost half of the profiles experienced net erosion while the other half experienced net accretion. In past years summer profiles have followed expected accretionary trends and developed full scale constructional profiles by the end of the season. This study period, however, there was not a full development of constructional profiles. This can be attributed to a combination of factors including: 1) uncharacteristically active longshore sediment transport induced by intense storm activity early on during the month of June, 2) variations in sediment supply related to dredging of the Kennebec River in September of 2011, and 3) enhanced erosion related to tidal influence as the Sprague River channel and the old Morse River Channel are anchored against the Cape Small headland, and the Popham Beach west dune ridge, respectively, preventing effective onshore transport throughout seemingly fair weather conditions. Only the West Bath House transect at Popham beach experienced accretion by welding of an off shore bar complex. However long-term trends have not yet been established as this sector of the study was just added in 2010.

The early fall period had extremely mild weather conditions up until October, at which point seven storms occurred. Three of the seven storms maintained enough power to influence the barrier complex. The period exhibited overall erosive trends across the complex, which is expected during the fall months. Although there was not an outstanding amount of storm activity, average wind speeds and wave heights increased from the summer period, as overall storm frequency increased, although the majority of storms were of lower intensity. Winter profile development was fostered by increased longshore sediment transport in comparison to the summer period. As no major storm events were record by weather data, nor influenced profile shape, the erosive trends which developed over this study period are attributed to a higher intensity hydraulic regime, rather than one specific storm event inducing short-term change.

During the late fall period two massive storm events took place. Hurricane Sandy, a southwesterly storm that coincided with spring tides on October 28th, 2012, and the Winter Storm Athena, a Nor'easter that coincided with neap tides on November 7th, 2012. Profile data exhibited extensive sediment transport. However, some profiles experienced net accretion, W1500 with 2256 m^3 net accumulation of sand, whereas other profiles such as Little Beach I experienced net erosion of 1008 m^3 net sand loss. A combination of factors could be responsible for such diverse trends, including: 1) upwelling by southwesterly wind and wave action from Hurricane Sandy, which dissipated as it approached the Maine coastline, therefore allowing sediment to be reworked onto the barrier and 2) enhanced longshore transport from the Winter Storm Athena's northwest winds and waves that approached the barrier at oblique angles. This caused erosion up drift and deposition down drift at the terminus of the westward and eastward longshore transport routes on the southwestern or northeastern Seawall spits. Furthermore sediment transport patterns were amplified as the two storms occurred within two weeks time. Therefore equilibration of the system to pre storm conditions failed, resulting in continued spit growth, as sediment was not fully reworked back onto the barrier. Although storm influence did not result in catastrophic erosion, the two storms did have impressive erosion potential during development. This is related to the ENSO cycle. This season's ENSO cycle is in a neutral phase, a phase conducive to high intensity development of extra tropical and tropical storms, where as the 2009 and 2010 seasons coincided with an ENSO positive phase. ENSO positive phases effectively prevents development of high intensity storm activity, and may explain the increases of powerful storm events passing through the study zone in 2012.

Finally, inlet migration proved to influence erosional trends along the complex, illustrated by both the Sprague River and the Morse River channels. When anchored against the Cape Small headland, spit growth is uninterrupted, and the pocket beaches are constantly influenced by the tidal prism of the inlet. Essentially, the inlet is preventing onshore sediment transport as well as eroding the pocket beach faces. Although the Morse River has remained in its western most location, the channel remnants from its pre 2010 location are still quite active. Therefore the Popham Beach face is in a similar situation as the two pocket beaches, where the old Morse River channel is preventing onshore transport and major bars from welding onto the beach face, as well as actively eroding the beach face. Furthermore, the Portland Tide gauge shows relative sea level rise rates at 1.82 mm +/- .11 mm/yr. Sea level rise in conjunction with massive storm events can prevent barrier beaches from re equilibrating to pre-storm conditions, therefore permanently removing sediment from the complex, and ultimately, causing barrier migration inland.

5.2 Future Work

As the Popham-Seawall complex is one of the few undeveloped barrier complexes left in Maine, it is essential to continue research projects along the barrier. Surveying is a time consuming process. Continuing profile data collection will allow comparison beyond just the seasonal and annual scale. However consolidation may be necessary as the project scope now consists of 14 transects, or monitoring the beach on a biannual scale may allow for all fourteen transects to be maintained without being overwhelming.

In conjunction with maintaining profile collection, mapping of the inlet channels and frontal dune ridges will open new doors for this project. Long term migrational patterns may be noticeable, as well as the relationship between inlet location and sedimentation patterns may be teased out more specifically.

Optimizing LIDAR data may prove an important way to analyze geomorphic change and its implications. LIDAR data is exceptionally high resolution, and will allow for features such as over wash fans, inlet breaching, and dune regression to be tracked on a long term scale. This study incorporated a basic estimation of net sand movement, which proved useful when related to storm activity. Using LIDAR data will allow for much more certainty in calculations, as well as 2D representation of changes between a profile set, rather than just cross sectional representation, which is also still useful.

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